Original Article

Effects of Hearing Loss on Interaural Time Difference Sensitivity at Low and High Frequencies

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Abstract

While many studies have reported a loss of sensitivity to interaural time differences (ITDs) carried in the fine structure of low-frequency signals for listeners with hearing loss, relatively few data are available on the perception of ITDs carried in the envelope of high-frequency signals in this population. The relevant studies found stronger effects of hearing loss at high frequencies than at low frequencies in most cases, but small subject numbers and several confounding effects prevented strong conclusions from being drawn. In the present study, we revisited this question while addressing some of the issues identified in previous studies. Participants were ten young adults with normal hearing (NH) and twenty adults with sensorineural hearing impairment (HI) spanning a range of ages. ITD discrimination thresholds were measured for octave-band-wide "rustle" stimuli centered at 500 Hz or 4000 Hz, which were presented at 20 or 40 dB sensation level. Broadband rustle stimuli and 500-Hz pure-tone stimuli were also tested. Thresholds were poorer on average for the HI group than the NH group. The ITD deficit, relative to the NH group, was similar at low and high frequencies for most HI participants. For a small number of participants, however, the deficit was strongly frequency-dependent. These results provide new insights into the binaural perception of complex sounds and may inform binaural models that incorporate effects of hearing loss.

Keywords

binaural hearing, sound localization, sensorineural hearing loss, binaural models

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Introduction

When locating broadband sounds, human listeners can make use of interaural time differences (ITDs) that are available in the temporal fine structure at low frequencies and in the amplitude envelope at high frequencies (for a recent review, see Hartmann, 2021). The relative importance of these regions may depend on the stimulus (e.g., frequency content, envelope characteristics) and the context (e.g., presence of masking, reverberation). For localizing speech in quiet and in noise, recent studies suggest that binaural cues at both low and high frequencies are given significant perceptual weight (Akeroyd & Firth, 2020; Baltzell et al., 2020a).

While many studies have reported a loss of sensitivity to fine-structure ITDs in listeners with hearing impairment (HI), relative to listeners with normal hearing (NH), few studies have focused on the perception of envelope ITDs in this population. The relevant studies fall into two classes. In one class of experiment, an ITD is applied selectively to the carrier or envelope of low-frequency sinusoidally amplitude-modulated (SAM) tones, such that effects of hearing loss on these two cues can be dissociated. Lacher-Fougère and Demany (2005) used stimuli with carriers at 250, 500 and 1,000 Hz, modulation rates of 20 or 50 Hz, and a fixed level of 75 dB SPL. They tested seven young NH adults and nine older HI adults. Thresholds were poorer in HI listeners overall, but especially for carrier ITDs. The ratio of HI/NH thresholds was 9.9 for the fine-structure task and 3.6 for the envelope task. Envelope ITD thresholds were correlated with audiometric thresholds in the HI group, raising the possibility that the reduced sensation level (SL) was a contributing factor, and control experiments in NH listeners confirmed that a reduction in SL increased envelope ITD thresholds (but not carrier ITD thresholds). King et al. (2014) used similar

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stimuli but presented them at a fixed SL to a large group of 46 listeners with a range of ages and hearing losses. They found that thresholds for carrier ITDs, but not envelope ITDs, were correlated with hearing loss. One problem with the experimental approach used by the aforementioned studies is that the envelope ITD must compete with the carrier ITD (which is always zero). If HI listeners are less sensitive to the carrier cue, they may be less influenced by it, which could effectively enhance their sensitivity to the envelope cue.

The second class of experiment avoids this confound by using high-frequency stimuli for which the temporal fine structure is not faithfully encoded by the auditory system and ITDs are assumed to be available only in the envelope. Hawkins and Wightman (1980) tested narrowband noises centered at 500 and 4,000 Hz. Their subject population was 11 young adults: three with NH, six with bilateral HI, and two with unilateral HI. For simplicity, the unilateral HI subjects are not considered here, and thresholds could not be obtained for one bilateral HI, leaving a group size of five. For stimuli presented at 85 dB SPL, thresholds were slightly poorer in the HI group at 500 Hz (34 vs. 17 µs, giving a HI/NH ratio of 2.0) but dramatically poorer at 4,000 Hz (mean 387 vs. 61 µs, or a HI/NH ratio of 6.3). When thresholds were compared at equal SL, the group differences were similar at 500 Hz (54 vs. 27 µs, HI/NH ratio of 2.0) and much reduced at 4,000 Hz (468 vs. 164 µs, HI/NH ratio of 2.9). Smoski and Trahiotis (1986) measured ITD detection using both low-frequency stimuli (500 Hz tones, 500 Hz narrowband noises) and high-frequency stimuli (4,000 Hz SAM tones, 4,000 Hz narrowband noises). Their subject population was six young adults (two NH and four HI). For stimuli presented at 80 dB SPL, HI thresholds were slightly poorer at 500 Hz (37 vs. 18 µs; HI/NH ratio 2.0), but dramatically poorer at 4,000 Hz (302 vs. 46 µs; HI/NH ratio 6.5). When stimuli were set to 25 dB SL, these differences were reduced at 500 Hz (53 vs. 42 µs; HI/NH ratio 1.2). At 4,000 Hz, although one HI subject could not be measured, thresholds for the remaining listeners were overall *better* for the HI group than the NH group (290 vs. 509 µs; HI/NH ratio 0.6). In a more recent study, Spencer et al. (2016) tested narrowband noises centered at 500 and 4,000 Hz in a group of relatively young listeners (10 NH, 11 HI). Stimuli were presented at a fixed level for the NH group (65 dB SPL) and at customized levels deemed to be "medium-high" in terms of loudness for the HI group. They reported a negligible effect of hearing loss at 500 Hz (68 vs. 58 µs; HI/NH ratio 1.2) and extremely variable results at 4,000 Hz with some unmeasurable thresholds in both groups (making ratios difficult to calculate). Bernstein and Trahiotis (2019) tested 10 NH listeners and eight listeners with so-called "slight" hearing loss (audiometric thresholds $\leq$ 25 dB HL at all frequencies but > 7.5 dB HL at 4 kHz). Their stimuli were narrowband noises at 500 Hz or transposed to 4,000 Hz at a fixed level of 67 dB SPL. They reported a comparable effect of hearing loss at the low and high frequency (HI/NH ratio 1.8 vs. 1.6). Overall, these studies suggest that the effects of hearing loss on sensitivity to envelope and fine-structure ITD sensitivity may be broadly similar, but firm conclusions are hard to draw.

In the present study, motivated in part by the inconclusive literature, we revisited the question of whether the effects of hearing loss on ITDs are similar at low frequencies (where they are carried predominantly in the fine structure) and at high frequencies (where they are carried in the envelope). The study was also motivated by our interest in natural signals such as speech that possess salient envelopes. We recently observed (Best & Swaminathan, 2019) that sensitivity to ITDs in speech is robust in HI listeners, even if their sensitivity is poor when measured with pure tones, and speculated that it may be in part due to preserved envelope coding in this population. Taking this idea even further, we wondered if hearing loss may in fact lead to *superior* envelope ITD sensitivity, as was hinted at in the limited data of Smoski and Trahiotis (1986). Such an effect may be related to the fact that HI listeners demonstrate enhanced sensitivity to modulation under some conditions (Jennings et al., 2018; Moore et al., 1996; Wallaert et al., 2017), which is generally attributed to a loss of cochlear compression.

We focused on stimuli that contain strong envelope fluctuations at high frequencies and thus have the potential to provide more salient envelope ITDs than those available in the studies cited above. Specifically, we chose temporally sparse noises ("rustles"), which contain aperiodic fluctuations that are ideal for ITD coding and have been shown to support extremely good ITD sensitivity in NH listeners (Ewert et al., 2012). We considered these stimuli to be a reasonable proxy for natural sounds like speech but with more controlled acoustics. To our knowledge, they have not been used in any previous study of binaural hearing in HI listeners. Since previous studies indicated a strong effect of level on envelope ITD sensitivity (see above and Dietz et al., 2013), we equated SL across listeners and tested two different SLs. Finally, we deliberately included both younger and older adults in our HI group, to help us draw conclusions about effects hearing loss that are independent of age.

Methods

Participants

Participants were 10 adults with audiometrically normal hearing (NH; ages 18–42 years, mean age 25) and 20 adults with bilateral sensorineural hearing impairment (HI; ages 18–90 years; mean age 50). The HI group included 10 younger adults who were well matched in age to the NH group (ages 18–45 years; mean age 27) and 10 older adults (ages 56–90, mean age 73). Hearing loss etiologies were unknown or genetic for the younger and middle-aged participants; those over 70 years of age exhibited typical age-related losses. Audiograms for the HI participants are shown in Figure 1. Their losses were relatively symmetric, with average across-ear differences of 5 dB and 6 dB at 500 Hz and 4,000 Hz respectively (and no greater than 20 dB in any participant at these frequencies). Hearing-aid wearers were required to remove their devices during testing. Participants over 70 years of age completed a standard Montreal Cognitive Assessment test to rule out severe cognitive decline (Nasreddine et al., 2005). Participants were paid for their time and gave informed consent. All procedures were approved by the Boston University Institutional Review Board.

Stimuli

Temporally sparse rustles were constructed following Ewert et al. (2012) and the reader is referred there for an extensive description. Briefly, Gaussian noise was generated at a sample rate of 44,100 Hz and random-duration temporal gaps were inserted between each noise sample. Gap durations were drawn from a uniform distribution between 0 and 3.62 ms, yielding a waveform kurtosis of 242 (cf. 3.16 for Gaussian noise). Broadband rustle stimuli were constructed with a duration of 500 ms, and a 10-ms zero-pad was applied prior to filtering. To separately examine ITD sensitivity to rustle stimuli at low and high frequencies, an octave-wide filter was applied centered at 500 Hz and 4,000 Hz, respectively. Filtering reduced the waveform kurtosis to 4.29 and 18.76, respectively. Shown in Figure 2, the filters were sufficiently steep (8^{th}-order Butterworth applied in the forward and backward direction) to ensure that the high-frequency rustle stimuli did not have significant energy below the canonical phase-locking limit for ITD perception at 1,500 Hz (see Brughera et al., 2013). However, to investigate the potential influence of low-frequency distortion products on ITD sensitivity, the 4,000-Hz rustle stimuli were presented with and without a continuous low-pass masking noise (1,500 Hz cutoff) that was interaurally uncorrelated. In addition to obtaining ITD sensitivity for low-frequency and high-frequency (with and without low-pass masking noise) rustle stimuli, ITD sensitivity was obtained for a 500-Hz pure tone and a "broadband" rustle stimulus (each with a duration of 500 ms). The broadband rustle stimulus was constructed by adding together the low-frequency and high-frequency rustle stimuli.

Stimuli were presented at two SLs: 20 and 40 dB SL. For the broadband rustle stimulus, high-frequency and low-frequency rustle stimuli were generated at the desired SL before being added together.

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 in front of a computer monitor and provided responses by interacting with a graphical user interface.

Testing began by measuring detection thresholds for each of the four stimuli (the 500 Hz tone, the 500 Hz rustle, the 4,000 Hz rustle, and the low-pass masking noise) using an adaptive tracking procedure. A three-alternative forced choice paradigm was used with a two-down/one-up tracking procedure. Initial step sizes were 5 dB, and after four reversals, the step size was changed to 2 dB. Correct answer feedback was provided on each trial. A track was completed after 12 reversals, and two tracks were completed for each stimulus. The detection threshold for each stimulus was determined as the average over the two tracks. The individual detection thresholds for the tone and the rustles were used to set each stimulus to 20 or 40 dB SL when measuring ITD thresholds. The low-frequency masking noise was presented at 10 or 30 dB SL, i.e., 10 dB SL below the high-frequency rustle stimulus. This noise was gated on 250 ms prior to the start of the trial, and was gated off 250 ms after the end of the trial.

ITD thresholds were measured for each of the five stimuli (500 Hz tone, broadband rustle, 500 Hz rustle, 4,000 Hz rustle, and the 4,000 Hz rustle with masking noise) using an adaptive tracking procedure. The task was a two-alternative forced choice lateralization task. On each trial, the target was presented in two intervals, separated by a 500-ms inter-stimulus interval. In the first interval, the ITD was always 0 μs, and served as a reference for the second interval. In the second interval, the ITD was either left-leading or right-leading, and the listener was instructed to indicate whether the target in the second interval was presented from the left or right of midline. The ITD was adaptively varied according to a two-down/one-up tracking procedure in $\log_{10}$ steps. The starting value was 0.5 ms and ITDs were initially varied in step sizes of 0.2 $\log_{10}$ units and subsequently in step sizes of 0.1 $\log_{10}$ units after the fourth reversal. ITDs were capped at a maximum value of 2 ms. Correct answer feedback was provided on each trial. A track was completed after 12 reversals. Tracks were organized into sets of five (one track per condition). Listeners completed three sets of tracks at 20 dB SL and three at 40 dB SL. For three of the HI listeners (one younger, two older) the stimuli at 40 dB SL were unpleasantly loud and that condition was not completed. The entire experiment, including detection thresholds and ITD thresholds, took approximately six hours and was spread over three visits to the laboratory. For each listener, data were pooled across the three tracks that were completed per stimulus (at each level), and psychometric functions were fit using the "psignifit" package (Schütt et al., 2016). Psychometric functions were fit through the log-transformed data, and thresholds were obtained by extracting ITD values corresponding to 75% correct on this function. Threshold estimates greater

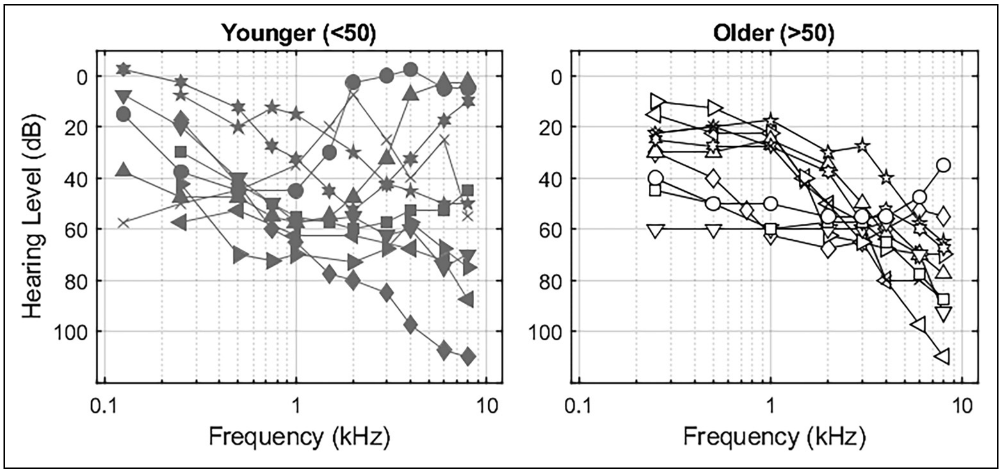

Figure 1. Across-ear average audiograms for the 20 HI participants. Younger (<50 years) and older (>50 years) adults are shown in separate panels.

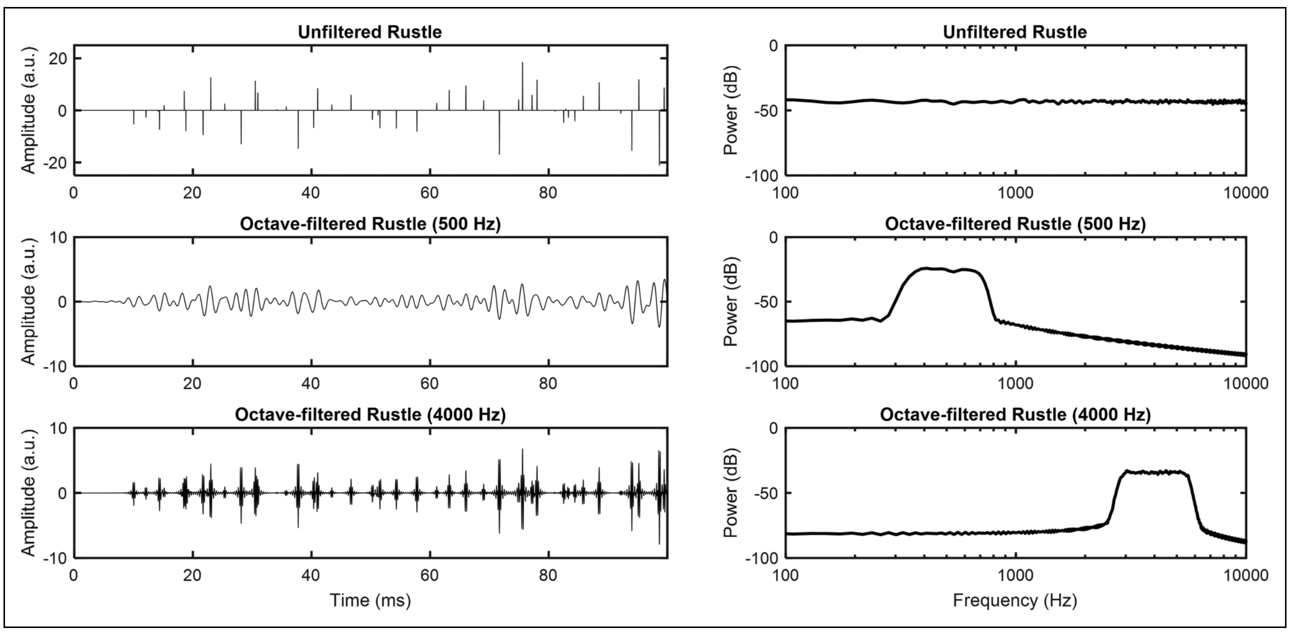

Figure 2. Sample stimulus waveform (left column) and spectrum (right column) for an unfiltered rustle (top row), a narrowband rustle centered at 500 Hz (middle row) and a narrowband rustle centered at 4,000 Hz (bottom row).

than the maximum presented ITD value of 2 ms were capped at 2 ms.

Results

Detection Thresholds

Figure 3 shows mean detection thresholds (in dB SPL) for each stimulus and each group. As expected, detection thresholds in the HI group were higher than in the NH group, and highly variable across listeners (consistent with the wide variety of audiograms in Figure 1).

ITD Thresholds

Figure 4 shows mean ITD thresholds for the two groups of participants in the different stimulus conditions. The thresholds show the expected effects of stimulus type (with better thresholds for the 500-Hz rustle than for the 500-Hz pure tone) and center frequency (with better thresholds at 4,000 Hz than at 500 Hz). The masking noise did not have a strong influence on thresholds for the 4,000-Hz rustle.

A linear mixed-effects model was fit to the ITD threshold data (thresholds were log-transformed for this analysis) and a three-way analysis of variance (ANOVA) was performed

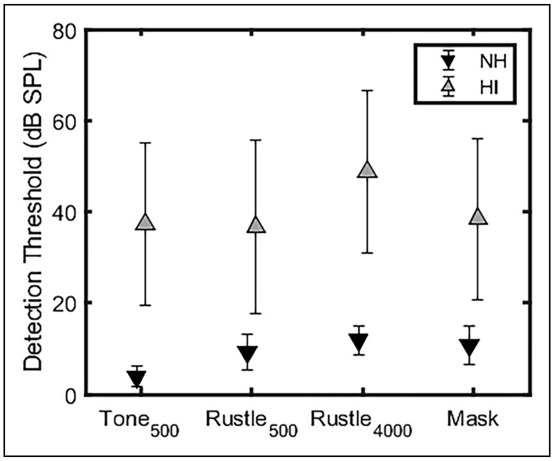

Figure 3. Detection thresholds for each stimulus used in the ITD experiment. Black and gray symbols show the NH and HI mean, respectively. Errorbars show across-subject standard deviations.

treating condition, hearing status, and presentation level as fixed effects, and treating subject as a random effect (random intercept). Given that age was not equally distributed across NH and HI listeners, it was not included as a predictor in the model. We observed a significant main effect of condition [$F(4, 255.3) = 21.9$, $p < .001$], and a significant main effect of hearing status [$F(1, 72.8) = 8.5$, $p = .005$]. Effective degrees of freedom were computed using the Satterthwaite method. We did not observe a significant main effect of presentation level [$F(1, 255.3) = 0.7$, $p = .41$]. We also did not observe any significant two-way interactions: condition*hearing status [$F(4, 255.3) = 1.18$, $p = .32$], condition*presentation level [$F(4, 255.3) = 0.7$, $p = .6$], hearing status*presentation level [$F(1, 255.6) = 0.002$, $p = .97$]. Finally, we did not observe a significant three-way interaction [$F(4, 255.3) = 0.17$, $p = .96$].

That the interaction between condition and hearing status was not significant suggests that the effect of hearing impairment on ITD sensitivity does not depend on frequency. To further support this null result, we ran the same model but only included the two conditions that were intended specifically to address the low versus high frequency question: 500-Hz rustle and 4,000-Hz rustle. The pattern of significance was the same, and once again the interaction between condition and hearing status was not significant [$F(1, 78.7) = 1.12$, $p = .3$].

Figure 5 shows ITD thresholds for the 500-Hz rustle and the 4,000-Hz rustle as a function of detection thresholds for the two stimuli. Individual younger and older HI participants are depicted by gray and white symbols, respectively, and mean values for the NH group are provided for reference (black symbols). For the low-frequency rustle, it can be seen that there were two older participants for whom ITD thresholds were essentially unmeasurable; these two participants also had very high detection thresholds (i.e., the most severe hearing loss in this region).

To investigate the relationship between ITD thresholds and detection thresholds in more detail, we fit separate mixed-effects models to each rustle stimulus, treating hearing loss and age as fixed effects, and treating subject as a random effect. Hearing loss was quantified separately for each rustle stimulus as the measured detection threshold for that stimulus. Since we did not observe significant effects of presentation level in the initial analysis, nor a significant interaction between presentation level and hearing status, the data were collapsed over presentation level for this analysis. Hearing loss and age were standardized (z-scored) prior to fitting the model. For the 500-Hz rustle, we found a significant main effect of hearing loss [$F(1, 16.2) = 8.3$, $p = .01$], a marginally significant main effect of age [$F(1, 16.1) = 4.4$, $p = .05$], and a significant interaction [$F(1, 16.1) = 5.7$, $p = .03$]. To investigate this interaction, we computed marginal effects of hearing loss for different ages, and found that the effect of hearing loss on ITD sensitivity increased linearly with age. For the 4,000-Hz rustle, we did not observe a significant main effect of hearing loss [$F(1, 15.7) = 0.36$, $p = .56$], nor a significant effect of age [$F(1, 15.3) = 0.92$, $p = .35$], nor a significant interaction [$F(1, 15.9) = 1.21$, $p = .29$].

To enable a direct comparison of the effects of hearing loss at low and high frequencies, the ratio of each individual HI listener's threshold relative to the corresponding group-mean NH threshold was calculated for the 500-Hz rustle and the 4,000-Hz rustle. This "HI/m(NH) ratio" is shown in Figure 6 with the symbols for individual participants connected by lines. Ratios are capped arbitrarily at a value of 60. A ratio of 1 (dotted line) means that a listener's ITD threshold was at the NH mean. A flat line indicates that the effect of hearing loss for a given individual is rather constant and does not depend heavily on the stimulus frequency. This appears to be the case for the majority of participants. The clear exceptions are the two older HI participants who had essentially unmeasurable thresholds (and undefined ratios) for the low-frequency stimulus. Other exceptions can be seen who exhibit a less dramatic but consistent asymmetry (i.e., a positive/negative slope at both SLs). On average, considering only the defined ratios, the HI/m(NH) ratios at 20 dB SL were 2.0 and 3.0 for 500 Hz and 4,000 Hz, respectively. Average ratios at 40 dB SL were 2.0 and 3.5. The fact that HI/m(NH) ratios are quite consistent for the majority of HI participants is consistent with the overall results presented earlier (see Figure 4), in which we found no significant interaction between condition and hearing status.

Discussion

It has been shown numerous times that listeners with sensorineural hearing loss have poorer ITD sensitivity on average relative to listeners with audiometrically normal hearing (Best & Swaminathan, 2019; Hawkins & Wightman, 1980;

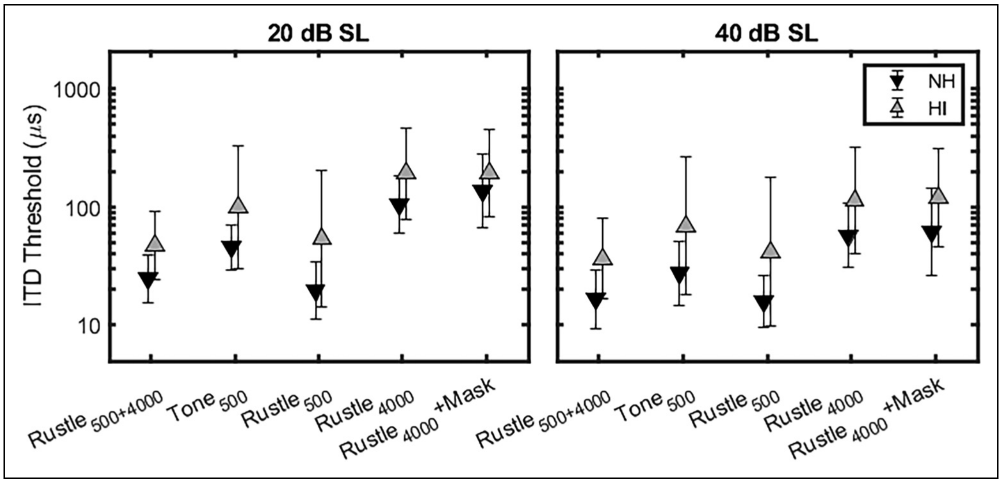

Figure 4. Mean ITD thresholds for each condition and group at 20 dB SL (left) and 40 dB SL (right). Black and gray symbols show the NH and HI mean, respectively. Error bars show across-subject standard deviations.

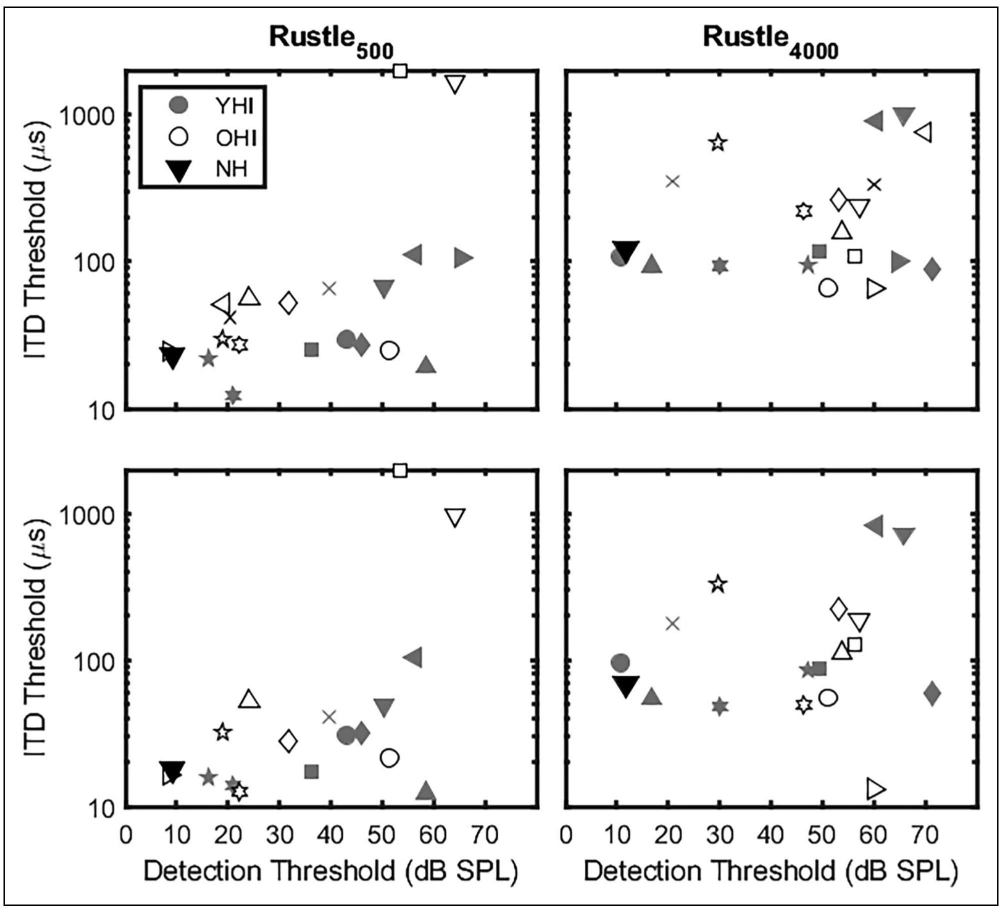

Figure 5. ITD thresholds as a function of detection thresholds for the 500-Hz rustle (left column) and 4,000-Hz rustle (right column) presented at 20 dB SL (top row) and 40 dB SL (bottom row). Black symbols show the NH mean. Gray and white symbols show individual younger and older HI listeners, respectively. Symbols and colors correspond to those in Figure 1.

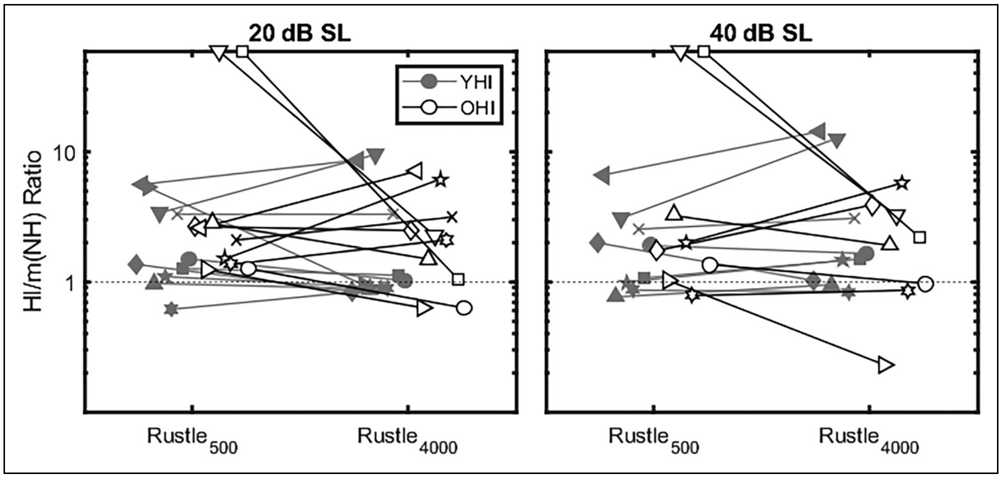

Figure 6. Individual HI/m(NH) ratios for the 500-Hz and 4,000-Hz rustle stimuli presented at 20 dB SL (left) and 40 dB SL (right). Gray and white symbols show individual younger and older HI listeners, respectively, and lines connect the two symbols for a given listener. Symbols are offset horizontally to improve visibility. Symbols and colors correspond to those in Figures 1 and 5.

King et al., 2014; Lacher-Fougère & Demany, 2005; Smoski & Trahiotis, 1986; Spencer et al., 2016). However, many details of this "ITD deficit" are still unclear, including whether it applies equally to ITDs carried in the fine structure and those carried in the envelope of complex sounds. Here we provide new data that enable a comparison of the effects of hearing loss for low-frequency stimuli (in which the ITD is carried primarily in the fine structure) and for high-frequency stimuli (in which the ITD is available exclusively in the envelope). To make this as fair a comparison as possible, we chose rustle stimuli that contain strong envelope fluctuations and thus provide salient ITDs at high frequencies. We also were careful to equate SL across the two frequencies and across participants to avoid confounding effects related to differences in detectability of the stimuli.

The results suggested that, at the group level, effects of hearing loss were similar at low and at high frequencies (Figure 4). Moreover, at the individual level, we found that a listener's ITD deficit (operationalized as the ratio of their threshold relative to the NH mean; Figure 6) tended to be consistent at low and at high frequencies. There were a few exceptions, in which the ITD deficit was larger at low or at high frequencies. This general result runs counter to several previous studies that reported stronger effects of hearing loss at high frequencies (Hawkins & Wightman, 1980; Spencer et al., 2016). We suggest that our result rests on the use of high-frequency stimuli with robust ITD cues and the careful equating of SL. It is also clear from the outliers in our data how very small samples of HI participants could lead to very different conclusions.

The finding that effects of hearing loss are broadly similar at low and high frequencies is somewhat surprising considering the fundamental differences in the nature of the ITD cue in these two regions. Indeed, the motivation for this study was to try to isolate effects on fine-structure ITDs (which dominate at low frequencies) and envelope ITDs (which are the only cue at high frequencies). To the extent that our rustle stimuli allowed us to separate these mechanisms, the results suggest that the encoding of fine-structure and envelope ITDs are equally susceptible to hearing loss. We did not find any evidence that envelope ITDs are more robust to hearing loss than fine-structure ITDs, as has been previously reported (King et al., 2014; Lacher-Fougère & Demany, 2005). We also did not find any evidence for *superior* envelope ITD sensitivity, as might be expected based on enhanced modulation sensitivity in this population (Jennings et al., 2018; Moore et al., 1996; Wallaert et al., 2017). This may be because the rustle stimuli have extreme modulations and subtle differences in the internal representations of those modulations are irrelevant.

The broad similarity of effects across frequency for these naturalistic stimuli is consistent with the view that the mechanisms supporting ITD processing are fundamentally equivalent across frequency. This view is based on a long history of binaural detection data and auditory nerve-based modeling (e.g., Colburn & Esquissaud, 1976; van de Par & Kohlrausch, 1997). More recently, it has been argued from a physiological standpoint (Joris & Trussell, 2018) that there are in fact two distinct ITD processing mechanisms subserved by two distinct brainstem nuclei. Specifically, while low-frequency ITDs are processed via a coincidence detection mechanism in the medial superior olive, high-frequency ITDs in transient stimuli are likely processed via "anti-coincidence detection" in the lateral superior olive. In any case, the encoding of ITDs at low and high frequencies is dependent on the faithful transmission of precisely timed inputs from the two ears. Within this framework, if hearing loss is accompanied by a loss of temporal precision in neural inputs across the tonotopic array, then one would expect similar ITD deficits at high and low frequencies.

A compatible view would be to assume that hearing loss corresponds to a frequency-independent increase in internal noise (Bernstein & Trahiotis, 2018, 2019).

Despite our primary conclusion, we did find subtle differences in the pattern of results for low- and high-frequency stimuli. For example, within our group of 20 HI participants, we found that ITD thresholds for the 500-Hz rustle were significantly related to detection thresholds (which can be considered a measure of the severity of their loss in that region) and marginally to their age. These relationships were not observed for the 4,000-Hz rustle. Most strikingly, the two participants who could not do the ITD task at 500 Hz had unremarkable ITD thresholds at 4,000 Hz (Figures 5 and 6). These individuals had poor low-frequency thresholds and were older in age. Our best explanation for this result is that ITD sensitivity for the 500-Hz rustle was dominated by fine-structure coding, which is known to be degraded by both age and hearing loss (Füllgrabe & Moore, 2018; Gallun et al., 2014). Specifically, the older listeners with severe losses may have been unable to capitalize on the fine-structure ITDs available at and above 500 Hz in the low-frequency rustle stimulus. More broadly, these results are also consistent with the idea that intact low-frequency hearing is particularly critical for the spatial perception of natural, complex sounds (Baltzell et al., 2020b; Best et al., 2010; Buchholz & Best, 2020; Noble et al., 1994).

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Declaration of Conflicting Interests

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