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Processing of temporal fine structure as a function of age

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Abstract

Objectives—The purpose of this study was to determine whether the processing of temporal fine structure diminishes with age, even in the presence of relatively normal audiometric hearing. Temporal fine structure processing was assessed by measuring the discrimination of inter-aural phase differences (IPDs). The hypothesis was that IPD discrimination is more acute in middle-aged observers than in older observers but that acuity in middle-aged observers is nevertheless poorer than in young adults.

Design—Two experiments were undertaken. The first measured discrimination of 0-and π-radian inter-aural phases as a function of carrier frequency. The stimulus was a 5-Hz sinusoidally amplitude modulated tone where, in the signal waveform, the inter-aural phase of the carrier was inverted during alternate modulation periods. The second experiment measured IPD discrimination at fixed frequencies. The stimulus was a pair of tone pulses where, in the signal, the trailing pulse contained an IPD. A total of 39 adults with normal audiograms below 2000 Hz participated: 15 younger, 12 middle-aged, and 12 older.

Results—Experiment 1 showed that the highest carrier frequency at which a π-radian IPD could be discriminated from the diotic, 0-radian standard was significantly lower in middle-aged listeners than young adults, and lower still in older listeners. Experiment 2 indicated that middle-aged listeners were less sensitive to IPDs than young adults at all but the lowest frequencies tested. Older listeners, as a group, had the poorest thresholds.

Conclusions—These results suggest that deficits in temporal fine structure processing are evident in the pre-senescent auditory system. This adds to the accumulating evidence that deficiencies in some aspects of auditory temporal processing emerge relatively early in the aging process. It is possible that early-emerging temporal processing deficits manifest themselves in challenging speech-in-noise environments.

Keywords

temporal processing; aging; inter-aural phase difference; fine structure

Introduction

Older listeners often exhibit difficulty following rapid changes in a sound. This difficulty is not entirely due to age-related loss of sensitivity to sound, but is also likely due to additional contributions from a spectrum of factors ranging from neural encoding deficits to declines in cognitive functions that are engaged when processing temporal events (for review, see Gordon-Salant 2006; Schneider, Pichora-Fuller et al. 2010). One ramification of this complexity is that the study of temporal processing in the senescent auditory system requires careful attention to the type of temporal event that is being assessed (Phillips 1995). Duration discrimination, gap

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detection, sensitivity to amplitude modulation, rhythm discrimination, detection of onset asynchrony, etc., all arguably fall within the purview of temporal processing assessment, yet each measure focuses on a distinct temporal feature. In this study the temporal feature of interest is fine structure, defined here as the on-going oscillations in pressure around ambient pressure within the audio frequency range. Fluctuations in the amplitude of the (relatively fast) fine structure give rise to the (relatively slow) envelope of sound and, in this sense, the fine structure 'carries' the envelope. The encoding of temporal fine structure is assumed to reflect the fidelity of physiological phase locking wherein the directional sensitivity of hair cell excitation is preserved in the discharge pattern of the neural response. Phase locking is predominantly a low-frequency phenomenon in that the ability of eighth nerve fibers to preferentially respond to a particular phase of the stimulus declines rapidly above about 1000 Hz (e.g., Kiang, Watanabe et al. 1965; Rose, Brugge et al. 1967).

Various psychophysical measures have been interpreted as reflecting fine structure coding. These include monaural measures of detection and discrimination of low-rate frequency modulation (Moore and Sek 1996; Lacher-Fougere and Demany 1998; Buss, Hall et al. 2004; Strelcyk and Dau 2009) and discrimination of the pitch of certain classes of complex harmonic sounds (Vongpaisal and Pichora-Fuller 2007; Moore, Hopkins et al. 2009; Moore and Sek 2009). Monaural speech measures that reflect fine structure coding include the recognition of speech that has been 'stripped' of its envelope (Lorenzi, Gilbert et al. 2006; Sheft, Ardoint et al. 2008), temporally jittered (Pichora-Fuller, Schneider et al. 2007) or processed to vary the frequency region or amount of fine structure information available (e.g., Hopkins and Moore 2009). Binaural measures that reflect – at least in part – fine structure coding include the binaural masking level difference (BMLD) (e.g., Eddins and Barber 1998; Strelcyk and Dau 2009) and the discrimination of inter-aural time differences (ITDs) which, for on-going tones, translate to inter-aural phase differences (IPDs) (e.g., Yost 1974; Lacher-Fougere and Demany 2005). Registration of IPDs is presumed to involve the comparison of phase-locked inputs from the two ears, a process that forms the basis of the coincidence detection model of binaural hearing (Jeffress 1948). The early observation that IPD sensitivity for pure tones is measurable only for frequencies less than about 1500 Hz (Klump and Eady 1956; Zwislocki and Feldman 1956; Nordmark 1967) is congruent with the physiological finding that the synchronization index for monaural phase locking declines with increasing frequency (e.g., Kiang, Watanabe et al. 1965; Rose, Brugge et al. 1967). The more rapid decline of IPD sensitivity with increasing frequency compared to that of phase locking can be accounted for by the physiological demonstration that the synchronization coefficient for inter-aural coincidence detection is the product of the synchronization coefficients for phase locking in each ear (Batra, Kuwada et al. 1997). Thus assessment of ITDs or IPDs provides a sensitive metric for neural synchrony.

Aging effects have been noted in binaural tasks that involve ITD and IPD processing. For example, reduced BMLDs in older listeners can be successfully modeled as being due to increased temporal jitter (Pichora-Fuller and Schneider 1992). For click trains, the ITD threshold is elevated in older listeners, particularly for low sensation levels (Strouse, Ashmead et al. 1998), but ITD sensitivity declines systematically throughout much of the adult age range, with deficits evident even in middle age (Babkoff, Muchnik et al. 2002). Aging effects in IPD-related tasks have also been observed for more frequency-specific stimuli. Ross et al. (2007) measured psychophysical discrimination of inter-aural phase inversion as a function of frequency in adult listeners of different ages. The task assessed the highest carrier frequency of a 40-Hz sinsuoidally amplitude modulated (SAM) tone at which a π-radian IPD could be discriminated from the diotic, 0-radian condition. Although there was a great deal of variability in the performance of middle-aged and older listeners, the general trend was a decline in the upper limit of the carrier frequency with age. The implication of this finding is that, if the discrimination of inter-aural phase reflects fidelity of physiological phase locking, the decline in the upper limit of the carrier frequency with age points to a concomitant decline in neural synchrony. This conclusion is supported by several electrophysiological and magnetoencephalographical (MEG) studies of sensitivity to inter-aural phase disparity (Ross, Fujioka et al. 2007; Ross 2008; Wambacq, Koehnke et al. 2009).

The possibility that deficits in neural synchrony are evident in the pre-senescent (middle-aged) auditory system is of particular interest to this investigation. Evidence is accumulating that temporal processing deficiencies are not restricted to older listeners but begin to emerge relatively early in the aging process (e.g., Grose, Hall et al. 2006; Helfer and Vargo 2009). In light of this interest in early emergence of temporal deficits, details of the Ross et al. (2007) study deserve especial scrutiny. In the MEG arm of that study, significant deficits in sensitivity to inter-aural phase inversion were demonstrated in middle-aged listeners, but complementary data from the psychophysical arm of the study were actually too variable to allow conclusive statistical analysis. This difference in inter-observer variability between the psychophysical and MEG findings is striking. The MEG measure of inter-aural phase sensitivity consisted of the elicitation of an acoustic change complex associated with the phase inversion (0-radian to π-radian) of the carrier frequency of a 40-Hz SAM tone; the inversion occurred midway through a 4-second stimulus during a modulation minimum. The measure of interest was the detection of a P1-N1-P2 complex elicited by the phase inversion. The results indicated an age-dependent reduction in the upper frequency limit of the carrier at which a change complex was evident. The variability within each of the three age groups (young, middle-aged, older) was equivalent and constrained, allowing the significance of the monotonic decline in frequency with age to emerge. In contrast, the corresponding psychophysical results were much more variable in the middle-aged and older groups. Here, the task consisted of the discrimination of two 40-Hz SAM tones on the basis of their inter-aural phase (0-radian or π-radian). Unlike the MEG stimulus where the phase inversion occurred within a single stimulus, the IPD was constant throughout each 1-second stimulus in the psychophysical task and the discrimination was made across observation intervals. Pronounced inter-observer variability is not an uncommon occurrence in psychophysical studies of IPD discrimination where the comparison occurs across observation intervals (e.g., Chung, Hall et al. 2004).

The purpose of the first experiment was to revisit the issue of IPD discrimination as a function of age but to use a psychophysical task that minimized inter-observer variability. The goal was to generate a more conclusive finding in terms of performance in middle age. The possibility investigated here was that IPD discrimination might be less variable in a task in which the phase change occurred within a stimulus rather than across stimuli. The approach taken was akin to that of Ross et al. (2007) in that it measured the highest carrier frequency of a SAM tone for which a dichotic stimulus could be discriminated from a diotic stimulus as a function of observer age. However, the novel implementation was that the phase transition (0-radian to π-radian) occurred multiple times within each signal such that the observer’s task was to discriminate the phase-dynamic signal from the static (diotic) standard. The expectation was that the use of dynamic signals would facilitate the discrimination of inter-aural phase. The focus of this study was on the pre-senescent emergence of deficits in temporal fine structure coding; therefore, young, middle-aged and older listeners with relatively normal hearing participated. The hypothesis was that IPD discrimination is more acute in middle-aged observers than in older observers but that acuity in middle-aged observers is nevertheless poorer than in young adults.

Exp. 1. Discrimination of 0-& π-radian IPD as a function of carrier frequency

Method

Participants—Three groups of listeners participated: (1) Younger (N = 13 [11females]; age range = 18–27 yrs; [mean = 22.2 yrs]); (2) Middle-aged (N = 10 [9 females]; age range = 40–

55yrs; [mean = 47.5 yrs]); and (3) Older (N = 10 [6 females]; age range = 63–75yrs [mean = 67.8 yrs]). All listeners had normal audiometric thresholds (≤ 20 dB HL) for the octave frequencies 250 – 2000 Hz.[1] On average, the thresholds for the three groups were also in the normal range at 4000 Hz, but six of the ten listeners in the older group exhibited a threshold within the range 25 – 40 dB HL at this frequency. Fig. 1 portrays the group mean thresholds.[2] Note that all listeners were selected to have symmetrical hearing; the average difference in threshold across ears was < 5 dB.

Stimuli—The stimuli were SAM tones, 800 ms in duration, presented at a level of 65 dB SPL through Sennheiser HD580 phones (Old Lyme, CT). The rate of modulation was 5 Hz, with a modulation depth of 100%, resulting in four periods of modulation during the stimulus. The starting phase of the sinusoidal modulator was $3\pi/2$ resulting in a modulation minimum at the onset and offset of the stimulus. No other onset/offset shaping was applied. The standard stimulus was diotic, with the carrier frequency in phase at the two ears. In the signal stimulus, the waveform was diotic during the first and third periods of modulation but underwent an inter-aural phase inversion during the second and fourth periods of modulation. This π-radian phase reversal occurred during the modulation minimum and so was inaudible to the observer. A schematic of the signal and standard waveforms is shown in Fig. 2. All stimuli were digitally generated using a Tucker-Davis Technologies (TDT, Alachua, FL) digital signal processing platform interfaced with custom Matlab (Mathworks, Natick, MA) code.

Procedure—The task was a 3-alternative, forced-choice (3AFC) procedure that incorporated a 3-down, 1-up adaptive rule that converged on the 79% correct point on the psychometric function. The independent variable was the carrier frequency of the SAM tone, which varied in steps of one-quarter octave. A threshold estimation track was terminated after 8 reversals in frequency direction and the final 6 reversal frequencies were geometrically averaged to yield a threshold estimate. This estimate indexed the highest frequency at which the signal, incorporating a phase reversal during alternate periods of modulation, could be discriminated from the diotic standard. At least four replications were collected per listener (with the exception of one younger and one middle-aged listener for whom only three replications were collected because of minimal variability across estimates). In all cases, final threshold was taken as the mean of all estimates.

Results and Discussion

The results for the three age groups are shown in Fig. 3 as a box-and-whisker plot. The unfilled rectangles represent data from this experiment; for comparison, psychophysical data derived from Ross et al. (2007) are plotted as shaded rectangles. Each rectangle encompasses the 25th-to-75th percentile, with the thick horizontal bar within each rectangle indicating the median. The caps on the vertical lines indicate the 10th and 90th percentiles. Focusing on the results from this study, two observations can be made. First, the range of performance is more extensive for the older listeners than for the two younger groups. This was due in large part to the poor performance of one listener who had particular difficulty with the task, generating a threshold of about 143 Hz, well below any other listener. The second observation is that performance declined across the three age groups.

[1]The one exception to this was an older observer who had a threshold of 30 dB HL at 250 Hz in one ear only. This observer was an above-average performer in both experiments.

[2]The mean audiograms in Fig. 1 are actually for all observers who participated in this study (Exps. 1 and 2). Whereas the majority of observers participated in both experiments, there was not complete overlap (six observers, 2 per age group, participated in Exp. 2 but not in Exp. 1). However, because the group mean audiograms for the Exp. 1 observers were highly similar to the group mean audiograms for the Exp. 2 observers, they have been collapsed for efficient illustration.

In order to assess the significance of the decline in performance with age, the results of this study were submitted to an analysis of variance (ANOVA) which indicated a significant effect of age group ($F_{2,30} = 13.2$; $p < 0.01$). Post-hoc comparisons using Tukey HSD indicated that all groups differed significantly from each other, including the middle-aged and younger groups ($p = 0.047$) and the middle-aged and older groups ($p = 0.048$). Repeating the analysis with the exclusion of the poorest-performing older listener negated the significant difference between the middle-aged and older groups, but both of these groups still performed more poorly than the younger listeners. These results therefore add further support to the hypothesis that the coding of temporal fine structure declines with age and that deficits are apparent in the middle-aged, pre-senescent auditory system.

One of the motivations of this experiment was to determine whether the use of phase-dynamic signals, where the inter-aural phase alternates within a single stimulus, facilitates IPD discrimination relative to the use of static-phase stimuli. The psychophysical procedure of Ross et al. (2007) employed static-phase stimuli, where the inter-aural phase was held constant within a single stimulus, and so a comparison of the data sets from the two studies in Fig. 3 is of interest. Three caveats concerning this comparison are that: (i) the age-range groupings were not completely coincident across the two studies, (ii) this study tracked the 79% correct point on the psychometric function whereas the Ross study tracked the 70% correct point, and (iii) the Ross paradigm used a fixed lower frequency limit which resulted in chance performance yielding thresholds of about 380 Hz. Nevertheless, it is apparent that the variability for the younger and middle-aged groups was less pronounced in this study than the Ross et al. study. The median threshold was also higher in this study across all three groups, although the highest (best) individual frequency thresholds in the Ross et al. study exceeded the best scores measured here for each age group. (Threshold comparisons across the two studies are cautionary given the different %-correct points being tracked.) A parsimonious interpretation of the two data sets is that the use of dynamic stimuli likely facilitates the performance of individual observers who might otherwise be prone to difficulty with the discrimination task.

In summary, this experiment demonstrates that the discrimination of IPD declines with age and that deficits are evident in middle-aged listeners. This suggests that detriments in temporal fine structure coding exist even in the pre-senescent auditory system. The approach of this experiment was to employ fixed IPDs (0-or π-radians) and to vary the SAM tone carrier frequency. In order to test the reverse configuration, a second experiment was undertaken wherein the stimulus frequency was fixed while the IPD was varied.

Exp. 2. IPD discrimination at fixed frequencies

Method

Participants—There was a large overlap between the listeners in this experiment and that of the previous experiment. However, in the younger group one listener from Exp. 1 did not participate but two new listeners did (N = 14). In the middle-aged and older groups, two additional listeners participated in each group (N = 12, respectively). The inclusion criteria in terms of audiometric thresholds remained the same as Exp. 1 and the mean audiograms shown in Fig. 1 include the data from the additional listeners.

Stimuli—The stimuli consisted of sequences of two 200-ms tone bursts separated by an interval of 50 ms. Each tone burst was shaped with raised-cosine onset and offset ramps. The duration of the onset ramp was 75ms whereas that of the offset ramp was 25 ms; the plateau duration was100ms. The relatively long onset ramp was imposed to discourage the listener from using tone onset asynchronies across the two ears (i.e., onset ITDs) as the decision cue rather than on-going IPDs. The standard stimulus consisted of a pair of diotic tone bursts. The signal consisted of a pair of tone bursts where the leading tone burst was diotic but an IPD (random lag/lead) was imposed on the trailing tone burst. During the signal, therefore, the leading tone burst gave a centralized image whereas the trailing tone burst resulted in a lateralized image that was shifted to the left or right at random. A schematic of the signal is shown in Fig. 4. Seven tone-burst frequencies were employed: 250, 500, 750, 1000, 1125, 1250 and 1500 Hz. (Note that the 1125-Hz frequency was added after data collection was completed on the first four observers, therefore this data point is missing for 2 younger and 2 middle-aged observers.) The presentation level was 65 dB SPL.

Procedure—The just-noticeable IPD was measured using a 3AFC procedure incorporating a 3-down, 1-up adaptive stepping rule. The initial step size for the time difference between ears was $\sqrt{2}$ and, after 2 reversals in IPD direction, this was reduced by its square root for the final step size. A threshold estimation track was terminated after 8 reversals in the time difference and the geometric mean of the final 6 reversals was taken as the threshold estimate for that track. At least three estimates were collected for each frequency, and the average of all estimates constituted the final threshold. Each threshold represented the time difference between ears in microseconds at which the dichotic tonal stimulus could be discriminated from the diotic stimulus at about the 79% correct level. The upper limit of performance for each frequency occurred when a time difference corresponding to π radians for that frequency could not be discriminated; that is, if a listener could not discriminate a diotic stimulus from one with an IPD of π radians then that listener was at chance performance for that frequency. Testing began in the lower frequencies and the order of frequencies was varied across listeners. However, once a frequency was identified at which the listener performed at chance level over multiple replications, systematic testing at frequencies higher than this was curtailed. That is, some ‘spot-checking’ of higher frequencies occurred, but complete blocks of replications were not collected. The rationale for this was that, having reached the upper frequency limit of performance, it was improbable that the listener would resume the ability to perform the task at still higher frequencies. Pilot testing confirmed this assumption. For purposes of tabulation, the time difference associated with ceiling performance was recorded for each listener at each of these (higher) untested frequencies.

Results and Discussion

The results are shown in Fig. 5 as a box-and-whisker plot that portrays threshold ITD for each stimulus frequency. Each rectangle encompasses the 25th-to-75th percentile, with the thick horizontal bar within each rectangle indicating the median. The caps on the vertical lines indicate the 10th and 90th percentiles. The unfilled rectangles represent the younger listeners, the striped rectangles the middle-aged listeners, and the shaded rectangles the older listeners. It can be seen that rectangles become compressed as the ITD approaches the value corresponding to a π-radian IPD for that frequency. In the extreme, the rectangles are compressed to horizontal bars when all listeners within an age group have reached the upper bound (e.g., at 1500 Hz). Several observations can be made from Fig. 5. First, performance was quite variable across listeners even within age groups. Second, the frequency at which performance converged upon the π-radian limit tended to vary with age. For example, it can be seen that most of the older listeners converged upon the limit at 1000 Hz (ITD limit of 500 μsec) whereas all listeners were unable to perform the task at 1500 Hz (ITD limit of about 333 μsec). Because it is difficult to discern from Fig. 5 the actual proportion of listeners in each age group who were at ceiling for each frequency, this is portrayed in Fig. 6 as a bar graph (younger: unfilled bars; middle-aged: striped bars; older: shaded bars). Here it is more apparent that the majority of older listeners reached performance limits at 1000 Hz. In contrast, the majority of middle-aged listeners did not reach ceiling until 1250 Hz and most of the younger listeners performed at ceiling only at the highest frequency tested of 1500 Hz. The third observation that can be made from Fig. 5 is that, for those frequencies where performance was within measureable limits, the younger listeners had the lowest median thresholds whereas the older listeners had the highest, with the middle-aged tending to be intermediate.

In order to assess the significance of the age effect, two separate analyses of variance (ANOVAs) were undertaken. The first compared performance of all three age groups for the frequencies 250, 500, and 750 Hz. As can be seen in Fig. 6, for these lower frequencies the majority of listeners in each age group were able to perform the task within the π-radian limit. The second ANOVA tested only the younger and middle-aged listeners but included the additional frequencies of 1000 Hz and 1125 Hz where the majority of these listeners could still perform the task. In both analyses, the log transforms of the data were used to better equate the variances. The results of the first analysis indicated a significant effect of age group ($F_{2,35} = 6.28$; $p = 0.005$), a significant effect of frequency ($F_{2,70} = 14.26$; $p < 0.001$), and a significant interaction between group and frequency ($F_{4,70} = 3.1$; $p = 0.021$). Analysis of the interaction term indicated that, at 250 Hz, the younger and middle-aged groups did not differ, but both groups differed from the older group ($p = 0.002$ and 0.026, respectively). Likewise at 500 Hz, the younger and middle-aged groups did not differ, but both groups differed from the older group ($p = 0.004$ and 0.032, respectively). At 750 Hz, however, the younger group differed from both the middle-aged and older groups ($p = 0.032$ and 0.001, respectively), and the middle-aged group no longer differed from the older group. This pattern of results suggests that deficits in temporal fine structure processing are evident even at low frequencies in older listeners and that deficits begin to emerge in middle-aged listeners in the mid-frequencies.

The second ANOVA tested the younger and middle-aged listeners at the frequencies 250 – 1125 Hz. As noted above, there were two missing data points for the 1125-Hz condition in each age group. For the purposes of analysis, the median threshold for each respective group was used in place of the missing points. The results of the analysis indicated a significant effect of age group ($F_{1,24} = 5.62$; $p = 0.026$), a significant effect of frequency ($F_{4,96} = 20.76$; $p < 0.001$), and a significant interaction between group and frequency ($F_{4,96} = 3.49$; $p = 0.01$). Analysis of the interaction term indicated that the younger and middle-aged groups did not differ at the two lower frequencies of 250 Hz and 500 Hz, but did at the frequencies of 750 Hz, 1000 Hz, and 1125 Hz. This pattern of results again suggests that deficits in temporal fine structure processing are evident in the pre-senescent auditory system.

These findings confirm that older listeners have reduced IPD sensitivity relative to younger and middle-aged listeners. Of greater interest is the observation that middle-aged listeners have poorer IPD sensitivity than younger listeners except at the two lowest frequencies. Given that IPD sensitivity reflects, at least in part, temporal fine structure coding, this pattern of results supports a decline in phase locking with age and that this decline is evident in the pre-senescent auditory system.

General Conclusion and Summary

The results of these experiments support the notion that neural synchrony, as reflected in psychophysical measurements, declines with age. Exp. 1 demonstrated that the highest carrier frequency at which a π-radian IPD could be discriminated from the diotic case declined systematically with age. Exp. 2 extended this finding to demonstrate that ITD acuity as a function of frequency also declined with age. Whereas ITD acuity in older listeners was poorer than in younger listeners, even the performance of middle-aged listeners diverged from that of younger listeners at all but the lowest frequencies tested. This pattern of results adds to the accumulating evidence that deficiencies in some aspects of auditory temporal processing emerge relatively early in the aging process. Recently, Helfer and Vargo (2009) showed that middle-aged listeners with normal audiograms performed more poorly than younger listeners in challenging speech-in-noise tests and that speech performance was strongly correlated with a temporal measure of gap detection. Moreover, the middle-aged listeners self-reported hearing difficulties in some situations to a greater extent than younger listeners. The possibility that early-emerging temporal processing deficits manifest themselves in challenging speech-in-noise environments is coincident with the observation that speech performance in reverberation declines systematically with age from a peak performance at about 27 years of age (Nabelek and Robinson 1982). It is possible that detriments in neural synchrony with age undermine binaural processing and that this, in turn, contributes to diminished speech-in-noise performance relatively early in the aging process.

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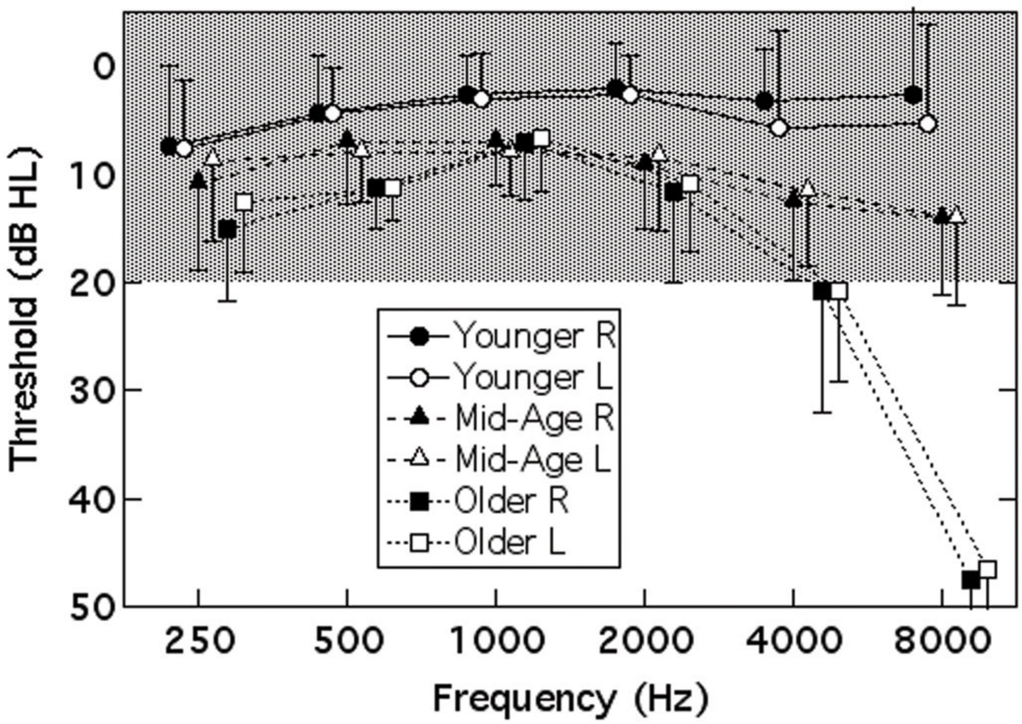

Fig. 1.
Average Left & Right ear audiograms for the 3 age groups. Error bars are 1 SD. Shaded area indicates region of normal audiometric thresholds.

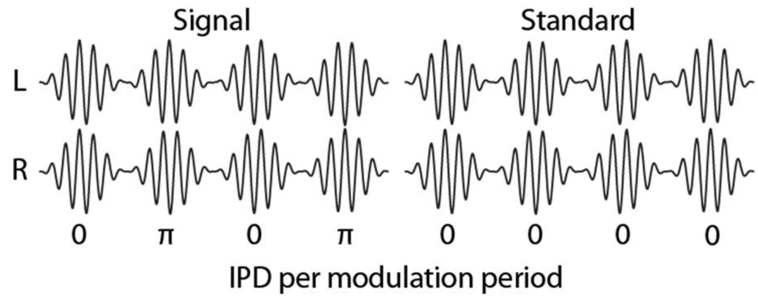

Fig. 2.
Schematic of the binaural SAM tone stimulus consisting of 4 periods of modulation. In the signal, the phase of the carrier was diotic for periods 1 and 3 but was inter-aurally inverted for periods 2 and 4. In the standard, the carrier was diotic throughout the stimulus.

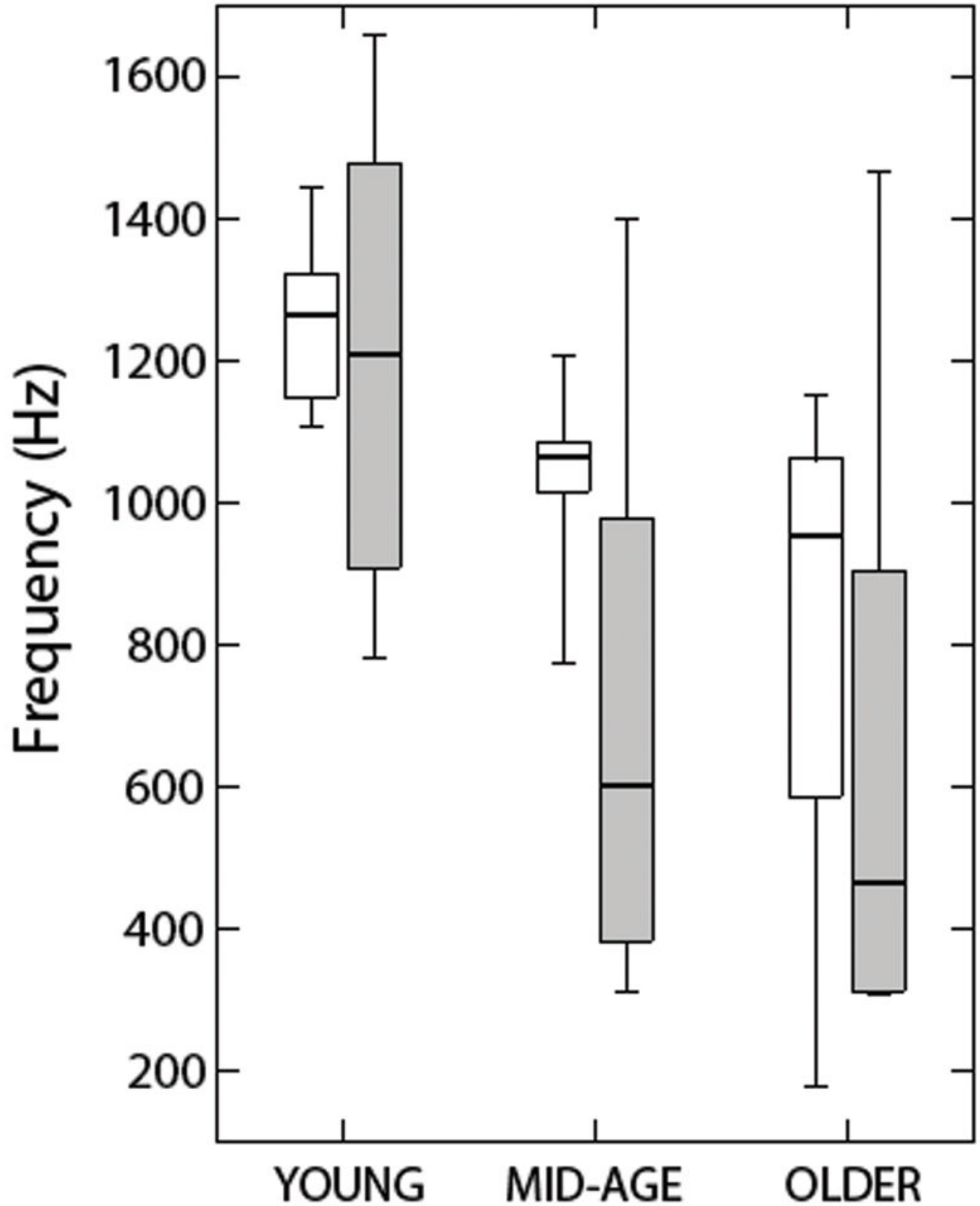

Fig. 3.
Upper frequency limit for discriminating 0- and π-radian IPD for each age group. Open rectangles are data from this study; shaded rectangles are from Ross et al. (2007). Each rectangle encompasses the 25^{th}-to-75^{th} percentile, with the thick horizontal bar within each rectangle indicating the median. The caps on the vertical lines indicate the 10^{th} and 90^{th} percentiles.

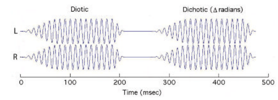

Fig. 4.
Schematic of the binaural signal showing the diotic leading pulse and dichotic trailing pulse. For this schematic, the phase shift (Δ radian) was set to π.

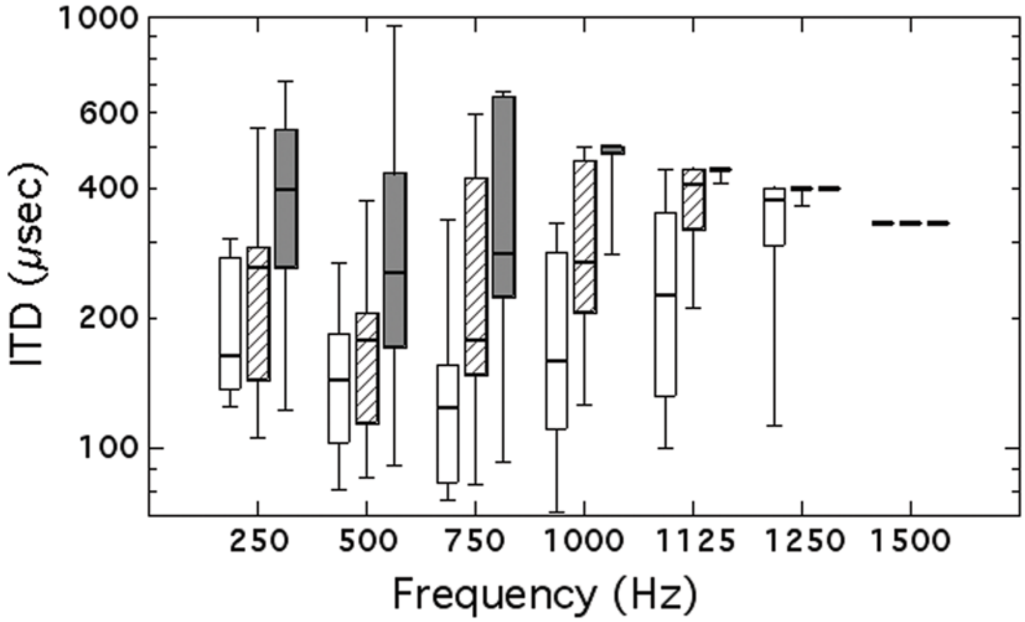

Fig. 5.
ITD threshold as a function of frequency for each age group (unfilled rectangle: younger; striped rectangle: middle-aged; shaded rectangle: older). Each rectangle encompasses the 25^{th}-to-75^{th} percentile, with the thick horizontal bar within each rectangle indicating the median. The caps on the vertical lines indicate the 10^{th} and 90^{th} percentiles. For each frequency, the upper bound of performance is the ITD associated with a π-radian difference across ears.

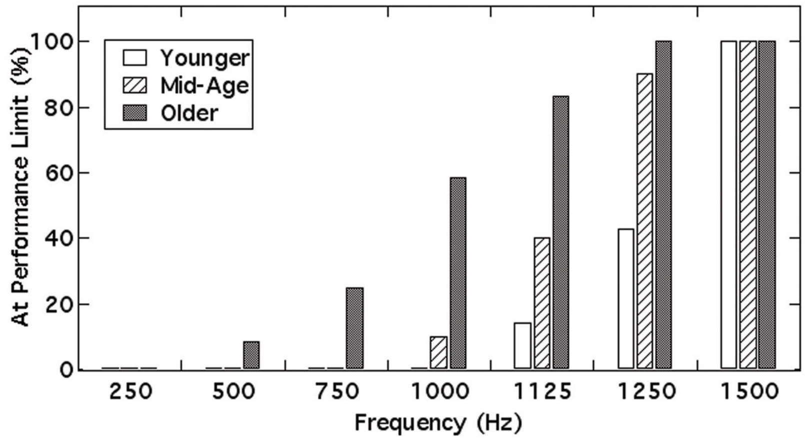

Fig. 6.

Percentage of listeners within each age group who were at the upper bound of performance for each frequency. Open bars: younger; striped bars: middle-aged; shaded bars (older).