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Measures of Hearing Threshold and Temporal Processing across the Adult Lifespan

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Abstract

Psychophysical data on hearing sensitivity and various measures of supra-threshold auditory temporal processing are presented for large groups of young (18–35 y), middle-aged (40–55 y) and older (60–89 y) adults. Hearing thresholds were measured at 500, 1414 and 4000 Hz. Measures of temporal processing included gap-detection thresholds for bands of noise centered at 1000 and 3500 Hz, stimulus onset asynchronies for monaural and dichotic temporal-order identification for brief vowels, and stimulus onset/offset asynchronies for the monaural temporal masking of vowel identification. For all temporal-processing measures, the impact of high-frequency hearing loss in older adults was minimized by a combination of low-pass filtering the stimuli and use of high presentation levels. The performance of the older adults was worse than that of the young adults on all measures except gap-detection threshold at 1000 Hz. Middle-aged adults performed significantly worse than the young adults on measures of threshold sensitivity and three of the four measures of temporal-order identification, but not for any of the measures of temporal masking. Individual differences are also examined among a group of 124 older adults. Cognition and age were found to be significant predictors, although only 10–27% of the variance could be accounted for by these predictors.

Keywords

aging; hearing loss; temporal processing; individual differences

It is well known that as adults age, a high-frequency sensorineural hearing loss often develops. This progressive hearing loss is so well established that an international standard has been adopted that describes both the expected median hearing loss with advancing age and the expected variability within a given age group (ISO, 2000). The prevalence of such hearing loss among older Americans has been estimated to be about 30% (Cruickshanks et al., in press).

Aside from the well-established progression of hearing loss in many older adults, the occurrence of other auditory deficits with advancing age has been less well established. For example, it is less clear if there are true age-related declines in auditory frequency resolution independent of that associated with the cochlear pathology underlying the observed hearing loss (e.g., Sommers & Humes, 1993). In general, however, there appears to be greater

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consensus that older adults may experience a variety of deficits in temporal resolution or temporal processing that are independent of the concomitant cochlear pathology. For example, several studies have demonstrated apparent age-related deficits in auditory gap-detection thresholds using relatively small samples of young and older adults (Moore et al., 1992; Schneider et al., 1994; Snell, 1997; Strouse et al., 1998; He et al., 1999; Schneider & Hamstra, 1999; Snell & Hu, 1999; Snell and Frisina, 2000). There is also auditory evoked-potential research in support of poor gap detection in the elderly (Boettcher et al., 1996). In addition to gap detection, several small-N group studies have demonstrated differences between the performance of young and older adults in various forms of auditory temporal masking (e.g., Zwicker & Schorn, 1982; Newman & Spitzer, 1983; Raz et al., 1990; Cobb et al., 1993; Gehr & Sommers, 1999; Halling & Humes, 2000). Furthermore, recent physiological measurements of auditory forward masking in animals and humans have shown age-related changes in forward masking unrelated to the concomitant effects of peripheral sensorineural hearing loss. This has been demonstrated both in single-unit recordings in the brainstem of laboratory animals (Walton, et al., 1998) and in brainstem evoked-potential recordings from humans (Walton, et al., 1999). Finally, psychophysical studies in humans also have documented age-related deficits in the auditory perception of temporal order (e.g., Trainor & Trehub, 1989; Humes & Christopherson, 1991; Fitzgibbons & Gordon-Salant, 1998, 2004, 2006; Shrivastav, Humes & Aylsworth, 2008). There is mounting evidence that auditory temporal processing may be impaired in older adults. As noted, most such studies, however, have made use of relatively small sample sizes ($N \leq 20$ per age group). The temporal phenomenon studied most frequently in older adults has been gap detection. In addition to somewhat mixed results regarding age effects, at least that are independent of concomitant cochlear pathology, a hallmark of these data has been the wide range of individual differences observed, especially among the older adults.

Human psychoacoustic studies have typically used just a young and an old age group sampling both ends of the adult lifespan. An exception to this is the study by Grose, Hall and Buss (2006) in which the gap-detection and gap-discrimination thresholds of a group of “middle-aged” adults, 40–55 years of age, were examined and contrasted to those of younger and older adults. There was some evidence of apparent age-related declines in temporal processing in the middle-aged group in this study.

Of course, an assumption underlying most of the studies of auditory temporal processing is that the behavioral measures obtained are, in fact, tapping performance specific to the auditory modality. This, however, can be mediated by the nature and complexity of the task, as well as the nature and complexity of the stimuli. Use of speech stimuli and an identification or recognition task in the study of temporal-order processing, for example, might involve amodal linguistic and cognitive processes more than a temporal-order discrimination task making use of tones. Likewise, use of longer sequences in a temporal-order task may be expected to involve more memory resources than a temporal-order task using only a two-stimulus sequence. To the extent that auditory temporal processing measures tap cognitive processes such as memory, speed of processing, and attention, and given the known age-related declines in these aspects of cognition (e.g., Salthouse, 1985, 2000; Verhaeghen & De Meersman, 1998a, 1998b), poorer performance of older adults on these tasks would be expected. Such performance declines, however, would not necessarily be attributable to poor auditory temporal processing.

In an effort to resolve some of these fundamental issues regarding age-related deficits in auditory temporal processing, a large-scale psychophysical project was undertaken at Indiana University in 2005. The entire project involves the measurement of a wide variety of temporal-processing measures in young, middle-aged, and older adults across three sensory modalities: hearing, vision, and touch (e.g., Humes et al., 2009). In addition, cognitive

measures are obtained from all participants. This project involves both large numbers of participants and many psychophysical measures obtained in three different laboratories. In addition to the first two authors of this paper, primary co-investigators on this multi-sensory project include Professor James Craig, who has expertise in tactile perception, and Professor Thomas Busey, who has expertise in visual perception, both of whom are in the Department of Psychological and Brain Sciences at Indiana University.

In the present paper, however, the focus is placed on the auditory measurements alone. Preliminary data on hearing thresholds and auditory gap-detection thresholds were published for young and older adults by Humes, Busey, Craig & Kewley-Port (2009). In the present article, these results will be updated by the inclusion of a more extensive data set for both young and older adults, as well as the addition of a smaller group of middle-aged adults. Fogerty, Humes & Kewley-Port (2009) have also published preliminary auditory temporal-order data for young and older adults. Once again, in the present article, these results will be updated by the inclusion of a more extensive data set for both young and older adults, as well as the addition of a smaller group of middle-aged adults. This article will also present the results for large groups of young, middle-aged, and older adults on several measures of temporal masking of speech identification. These preliminary data have not been published previously and these measurements will be documented in more detail below. Finally, the results from the older adults, the only age group for which there is a sufficient sample size thus far, will be pooled across all temporal-processing measures to examine the associations among these phenomena in older adults, as well as factors that might underlie individual differences in performance among older adults.

Methods and Materials

A. Participants

This report includes data collected across three phases. The three phases progressed in sequence and, ideally, all participants will complete all three phases. As of this writing, however, each phase contained a separate, but overlapping, sample of participants from each of three age groups: young, middle-aged, and older adults. Table 1 summarizes the sample sizes of each of the three age groups and phases included in this article and also provides a similar breakdown of the portion of each dataset published previously. In addition, a fourth sample of participants was comprised of one group of older adults who had completed all three phases. Phase I had the largest sample of participants [$N = 339$, 202 females and 137 males; 122 young, mean age 22.3 y ($SD = 3.0$ y); 45 middle-aged, mean age 48.3 y ($SD = 4.7$ y); 172 older, mean age 70.4 y ($SD = 6.6$ y)] and measures of auditory threshold and gap-detection threshold were obtained from these individuals. Phase II had the next largest sample [$N = 265$, 159 females and 106 males; 76 young, mean age 22.6 y ($SD = 3.4$ y); 32 middle-aged, mean age 48.7 y ($SD = 5.0$ y); 157 older, mean age 70.7 y ($SD = 6.7$ y)] and represents those individuals who proceeded to complete a series of temporal-order identification measurements. The sample for Phase III [$N = 215$, 131 females and 84 males; 62 young, mean age 22.3 y ($SD = 3.3$ y); 24 middle-aged, mean age 49.5 y ($SD = 4.7$ y); 129 older, mean age 70.8 y ($SD = 6.8$ y)] represents those who proceeded to complete a series of temporal-masking measurements for speech identification. Finally, the fourth set of participants was the smallest in number [$N = 124$, 70 females and 54 males; mean age 70.7 y ($SD = 6.9$ y)] and is comprised of those older adults who had completed all three phases listed above. This sample was used to examine individual differences in auditory temporal processing among the older adults. For each of the first three samples of participants described above, Chi-square testing indicated no significant differences ($p > .05$) in gender distribution across the three age groups.

Selection criteria for this study included: age (young: 18–35 y; middle-aged: 40–55 y; or older: 60–89 y), a Mini-Mental Status Exam (MMSE, Folstein, Folstein, and McHugh, 1975) score ≥ 25 , and specific hearing sensitivity requirements. Maximum hearing thresholds for air conducted pure-tones were not to exceed the following limits in at least one ear: 40 dB HL (ANSI, 2004) at 250, 500, and 1000 Hz; 50 dB HL at 2 kHz; 65 dB HL at 4 kHz; and 80 dB HL at 6 and 8 kHz. It was also required that there be no evidence of middle ear pathology (air-bone gaps < 10 dB and normal tympanograms). Listeners were paid for their participation. Informed consent was obtained from all participants in this study. All participants who met the selection criteria completed a full WAIS-III (Wechsler, 1997) cognitive assessment. This included thirteen standard subtests and two optional subtests of incidental learning. Once this testing was completed, auditory testing was scheduled.

B. General procedures and equipment

General features of the psychophysical methods and equipment common to all three phases are reviewed first. This is followed by a description of methods unique to each phase of testing.

All auditory testing was completed in a sound-attenuating booth meeting the ANSI S3.1 standards for “ears covered” threshold measurements (ANSI, 2003). Two adjacent subject stations were housed within the booth. Each participant was seated comfortably in front of a touch-screen display (Elo Model **1915L**). The right ear was the test ear for all monaural measurements in this study, except for six older listeners who were tested using their left ear due to right ear thresholds exceeding the inclusion criteria. (Since most of the auditory measures in this project were monaural, the inclusion criteria involving hearing loss only required one ear to meet these criteria and, in most cases, the right ear qualified for testing.)

Stimuli were generated offline and presented to each listener using custom MATLAB software. Stimuli were presented from the Tucker-Davis Technologies (TDT) digital array processor with 16-bit resolution at a sampling frequency of 48,828 Hz. The output of the D/A converter was routed to a TDT programmable attenuator (PA-5), TDT headphone buffer (HB-7) and then to an Etymotic Research 3A insert earphone. Each insert earphone was calibrated acoustically in an HA-1 2-cm³ coupler (Frank & Richards, 1991). Output levels were checked electrically just prior to the insert earphones at the beginning of each data-collection session and were verified acoustically using a Larson Davis model 2800 sound level meter with linear weighting in the coupler on a monthly basis throughout the study. Prior to actual data collection in each experiment, all listeners received 10–30 practice trials to become familiar with the task. These trials could be repeated a second time to ensure comprehension of the tasks, if desired by the listener, but this was seldom requested.

Adaptive tracking procedures were used in Phase I and Phase III experiments. The step size used to adjust the signal from trial to trial varied with the number of reversals during a given adaptive run. Phase II used a method of constant stimuli. All responses were made on the touch screen and were self paced. Correct/incorrect feedback was presented after each response during experimental testing. Further methodological details, specific to each phase of the study, follow.

C. Phase I: auditory thresholds and gap-detection thresholds

1. Stimuli Phase I—Auditory thresholds were measured for three pure-tone frequencies, 500, 1414 and 4000 Hz. Stimuli were 500 ms in duration from onset to offset and had 25-ms linear rise-fall times. The maximum output for the pure-tone stimuli was 98, 100 and 101 dB SPL at 500, 1414 and 4000 Hz, respectively. Further attenuation was provided via the

programmable attenuator under software control during the measurement of auditory thresholds.

Two auditory gap-detection measurements were made, each with a different 1000-Hz wide band of noise. These noise bands served as the stimuli with one band centered arithmetically at 1000 Hz (500–1500 Hz) and the other centered at 3500 Hz (3000–4000 Hz). Each noise band had a duration from onset to offset of 400 ms with 10-ms linear rise-fall times. A catalog of 16 different noise bands was generated for each frequency region. When a temporal gap was present in a noise band it was presented 300 ms post stimulus onset. Gap durations varied from 2 to 40 ms in steps of 2 ms and were generated by zeroing the waveform at that temporal location which necessitated the use of a background noise that covered a broad spectrum. This ensured that the cue available to the listener for gap detection was temporal and not spectral in nature. The spectrum level of the background noise was adjusted to be 12–15 dB below that of the stimulus noise bands. The background noise began slightly before the first interval and ended slightly after the last interval for a total duration of 2.4 seconds. An overall presentation level of 91 dB SPL was used for each noise band and for all listeners in this study. A relatively high presentation level was used given the likelihood of significant threshold elevations in many of the older adults, especially at the higher frequencies. Additional details of stimulus construction and calibration for Phase I can be found in Humes et al. (2009).

2. Procedures Phase I—Threshold measurements were completed prior to gap-detection measurements for all listeners. For measures of threshold sensitivity, an adaptive two-interval, two-alternative forced-choice paradigm was employed. Listeners simply selected the interval (marked by a rectangular box on a visual display) that contained the signal with an a priori probability of 0.5 that the signal would be in either interval 1 or interval 2. Signal amplitude was varied adaptively from trial to trial to bracket the 70.7% and 79.3% percent-correct points on the psychometric function using two interleaved tracks (Levitt, 1971). Three estimates each of 70.7 and 79.3 percent correct performance were obtained for a given signal frequency. In most cases, these six performance estimates were averaged to provide a single threshold estimate corresponding to approximately 75% correct on the psychometric function. For threshold measurements, frequencies were tested in the same order for all participants: 500 Hz, then 1414 Hz, and finally, 4000 Hz.

For measures of gap-detection thresholds, gap duration was varied using the same interleaved adaptive tracking procedures as those described for the threshold measurements, including performance levels tracked (70.7% and 79.3%). In addition, for these measurements, a three-interval, two-alternative forced-choice paradigm was used as described more fully in Humes et al. (2009). The stimulus waveforms in a given trial were identical except that a temporal gap had been inserted into the stimulus presented during comparison intervals 1 or 2. The specific noise-band waveform used on a given trial, however, was randomly selected among the 16 available in a stimulus catalog. The listener's task on each trial was to select the comparison interval that contained the gap or that differed from the standard (which never contained a gap). All listeners completed gap-detection measurements at 1000 Hz before beginning data collection at 3500 Hz.

D. Phase II: temporal-order tasks

1. Stimuli Phase II—Four confusable vowel stimuli / I, ε, a, u / were recorded by a male talker in a sound-attenuating booth using an Audio-Technica AT2035 microphone. Vowels were produced in a /p/-vowel-/t/ context. Productions of four vowels that had the shortest duration, $F_2 < 1800$ Hz, and good identification during piloting were selected for stimuli. Stimuli were digitally edited to remove voiceless sounds, leaving only the voiced pitch

pulses, and modified in MATLAB using STRAIGHT (Kawahara, Masuda-Katsume, and Cheveigne, 1999) to be 70-ms long with a fundamental frequency of 100 Hz. Stimuli were low-pass filtered at 1800 Hz and normalized to the same RMS level. Low-pass filtering was used to minimize the influence of possible high-frequency hearing loss of the older adults on their vowel identification performance.

The system was calibrated using a calibration vowel of the same RMS amplitude as the test stimuli, but with a duration of 3 seconds. A single stimulus presentation measured 83 (± 2) dB SPL and a presentation of two overlapping stimuli measured 86 (± 2) dB SPL.

2. Procedures Phase II—All listeners passed an identification screening of the four vowel stimuli in isolation with at least 90% accuracy on one of up to four 20-trial blocks in their test ear. This was to ensure that listeners would be able to complete the subsequent auditory temporal-order measures which were targeting identification performance of either 50 or 75 percent correct (see below). If participants did not reach this 90% identification accuracy criterion during screening, they were re-screened on a separate day. Participants ultimately unable to reach this criterion were dismissed from further auditory testing.

All listeners completed four experimental tasks in the following order: Monaural 2-item Identification (Mono2), Monaural 4-item Identification (Mono4), Dichotic 2-item Vowel Identification (Dich2), and Dichotic 2-item Ear Identification (D_Ear). A schematic illustration of the stimulus sequences used in each of these four tasks is provided in the top three rows of Figure 1. The first task, Mono2, required participants to identify the order of two vowels presented monaurally to the test ear. The second task, Mono4, presented a sequence of four vowels to the test ear. Two dichotic tasks were also completed. Dich2 was analogous to Mono2 with the exception that each of the two vowels was presented to a different ear, with the ear that was presented first randomized. D_Ear used the same stimulus presentation as Dich2, except listeners were only required to identify the ear that received the first stimulus. Additional details of the temporal order stimuli and procedures are found in Fogerty et al. (2009).

For all four tasks, the same vowel was never repeated twice in a row. The Mono4 task had the additional stipulation that each sequence must contain at least three of the four vowel stimuli. For the three vowel-identification tasks, listeners were required to identify using a closed-set button response the correct vowel sequence exactly (i.e., each vowel in the order presented) for the response to be judged correct. The ear-identification task, D_Ear, only required the listener to identify which ear (“Right” or “Left”) was stimulated first.

The dependent variable measured was the stimulus onset asynchrony between the presented vowels. The minimum stimulus onset asynchrony values were required to begin at or above 2 ms to ensure a sequential presentation for the stimuli. For the four-item sequences, the stimulus onset asynchrony defined the onset asynchrony between successive stimulus pairs in the sequence. For example, a stimulus onset asynchrony of 10 ms indicates that the onset of the second vowel followed the onset of the first vowel by 10 ms, the onset of the third vowel followed the second vowel by 10 ms and the onset of the fourth vowel followed the onset of the third vowel by 10 ms. All tasks used the method of constant stimuli to measure the psychometric function relating percent-correct identification performance to stimulus onset asynchrony. Threshold was defined as 50% correct (75% correct for D_Ear). Experimental testing was conducted in two stages because of large variability between listeners. The first stage consisted of a preliminary wide-range estimate of stimulus onset asynchrony threshold (i.e., using a large step size, 25 ms), while the second stage consisted of narrow-range testing centered at an individual's estimated wide-range threshold (i.e., using a smaller step size, 10 or 15 ms) to provide the actual stimulus onset asynchrony

threshold estimates reported in the results. In the end, each threshold estimate for each task was based on three valid narrow-range estimates that were averaged together for analysis, resulting in a total of 216 (Mono2), 288 (Mono4), or 432 (Dich2, D_Ear) trials per threshold estimate.

E. Phase III: temporal-masking tasks

1. Stimuli Phase III—The vowel stimuli used in the masking tasks were edited from the vowel stimuli used in Phase II. Earlier vowel masking experiments by Dorman et al. (1977) indicated that the 70-ms stimuli in Phase II would be too long to observe masking effects for young listeners. Therefore, 40-ms vowels were edited from each 70-ms vowel by deleting the first and last two pitch pulses (10 ms each). Other than the shortened duration, the stimuli used in Phase III were identical to those used in Phase II.

Two masker types were chosen: a pattern masker generated from the vowel stimuli and a noise masker generated digitally as a speech-shaped noise. To generate the pattern masker, the four 70-ms vowel stimuli were overlapped in time with staggered onsets, repeating each vowel four times, and digitally added together. To generate the noise masker, first the long-term spectrum of the pattern masker was calculated using the Welsh algorithm in MATLAB. A 127-point FIR filter was closely matched to the long-term spectral shape. This filter was applied to a digitally-generated, normally-distributed, noise waveform in MATLAB. Both pattern and noise maskers were RMS normalized to the calibration vowel. Sixteen unique 200-ms maskers of each type were generated and scaled. All maskers were low-pass filtered at 1800 Hz and 2-ms onset and offset ramps were applied to each masker waveform. The resulting waveforms were stored in either the pattern or noise catalogue for later use.

2. Procedures Phase III

Although participants had considerable experience listening to the 70-ms vowels in Phase II, Phase III started with presenting vowels 10 times each in a random-order screening task (after initial familiarization). Before starting the masking experiments, at least 60% identification accuracy was needed or the screening task was repeated.

There were four basic temporal masking tasks, all combinations of forward and backward masking with either the pattern or noise maskers. In addition, two different masker signal levels (based on pilot data) relative to the vowel level of 83 dB SPL were used to avoid either chance or perfect performance for most listeners. This resulted in eight temporal-masking conditions. On each trial, one of the 16 masker files from the pattern or noise catalogues was randomly selected. The vowel and the masker waveforms were added and presented to one ear, with a temporal separation between vowel and masker between 0 ms (simultaneous masking) and 250 ms as shown schematically in the bottom row of Figure 1. The measure of the temporal separation in ms between vowel and masker was based on stimulus onset asynchrony in backward masking and on stimulus offset asynchrony in forward masking. On each trial, one vowel and mask was presented for a specified stimulus onset asynchrony and the listener's task was to identify the vowel correctly.

Listeners identified the vowel heard using one of the four vowel responses similar to Phase II. Three estimates of each stimulus onset/offset asynchrony were made for the 50% and 70.7% correct performance level, using two interleaved tracks (Levitt, 1971) as in Phase I. These six performance estimates corresponding to 61% correct performance on the psychometric function were averaged for each of the 8 conditions. Stimulus onset/offset asynchrony was initially set to 150 ms for all masking conditions. The initial step size was 12 ms, and the final one was 4 ms. The lowest stimulus onset/offset asynchrony value was 0 ms and the experiment was terminated when the asynchrony exceeded 250 ms. Otherwise

the stopping rules were 9 reversals or a maximum of 100 trials and thresholds were calculated from the last 7 reversals.

Results

A. Phase I: Hearing and Gap-Detection Thresholds

Figure 2 shows scatterplots of individual hearing thresholds for 500 Hz (top), 1414 Hz (middle) and 4000 Hz (bottom) from each of the three age groups plotted as a function of participant age. At each frequency, a between-participant analysis of variance was performed to examine the effect of group with follow-up Bonferroni-adjusted t-tests conducted whenever a significant effect of group was observed. At all three frequencies, there was a significant ($p < .001$) effect of group (500 Hz: $F(2, 335) = 72.0$; 1414 Hz: $F(2, 336) = 74.9$; and 4000 Hz: $F(2, 335) = 204.6$). Follow-up t-tests on all three paired comparisons at each frequency revealed that the older adults had significantly ($p < .05$) higher hearing thresholds than the other two age groups at 500 Hz and that all three groups differed from one another at the two higher frequencies.

Figure 3 shows similar scatterplots of individual gap-detection thresholds at a center frequency of 1000 Hz (top) and 3500 Hz (bottom) as a function of participant age. Once again, effects of age group were examined initially with an ANOVA. A significant effect of age group was observed only at the higher center frequency (3500 Hz: $F(2, 336) = 9.3$, $p < .001$), although the effect of group at 1000 Hz was close to achieving statistical significance ($p = 0.07$). Follow-up Bonferroni-adjusted t-tests revealed that only the older group differed significantly from the young group at 3500 Hz.

Correlations were computed between participant age and each of the five hearing or gap-detection thresholds. Given the large sample size ($N = 339$), correlation coefficients of small magnitude will still achieve statistical significance ($p < .01$). In fact, as shown in Table 2, all five dependent measures were significantly correlated with age. Clearly, though, the magnitudes of the correlations with age are considerably greater for threshold sensitivity than gap-detection threshold. Table 2 also depicts the correlations among the five dependent measures themselves. Again, all are statistically significant ($p < .01$). The pattern apparent in this correlation matrix is for the correlations within the same task, but at different frequencies, to be more strongly correlated ($0.56 < r < 0.75$) than across tasks ($0.21 < r < 0.38$). Partial correlations also were computed between age and gap-detection threshold, controlling for hearing threshold, and between hearing threshold and gap-detection threshold, controlling for age. The partial correlation between age and gap-detection threshold was -0.03 at 1000 Hz (controlling for hearing thresholds at 500 and 1414 Hz) and -0.01 at 3500 Hz (controlling for hearing threshold at 4000 Hz) whereas that between hearing threshold and gap-detection threshold was 0.13 and 0.23 (controlling for age) at 1000 and 3500 Hz, respectively. These values indicate that the weak, but significant, correlations between gap detection and age are mediated by hearing loss and not true associations with age.

B. Phase II: Temporal Order Identification for Vowels

Figure 4 provides scatterplots of the individual data on the temporal-order identification tasks for each of the three age groups. The top two panels depict stimulus onset asynchronies for vowel sequences presented monaurally, with vowel pairs on the left and four-vowel sequences on the right. Note that the scale on the ordinate in the latter condition differs from that in the other three panels. This was necessary to accommodate the spread of the data in the monaural four-item task. The bottom two panels depict stimulus onset asynchronies for vowel pairs presented dichotically with the vowel identification task on the

left and the ear-identification task on the right. Recall that the targeted performance level for the ear-identification task (75% correct) differed from that of the other three temporal-order identification tasks (50% correct) due to differences in chance performance across tasks. From visual inspection, onset asynchronies for the monaural two-item identification task are lowest for all age groups with smaller differences across the other three age groups. In addition, visual inspection reveals a trend of stimulus onset asynchrony increasing with age in all four panels, but with considerable overlap among the three age groups.

The focus here is on group differences, rather than task differences. The latter have been examined in detail with a somewhat smaller dataset by Fogerty, Humes & Kewley-Port (2009). Except for the easiest monaural two-item identification task, for which less than 1% of the data were missing, the other three dependent measures had from 4.5–11.7% of the data missing, most often because the task could not be performed (typically by the older adults). As a result, non-parametric tests based on medians and ranks were performed on these data when examining the effects of age group so as not to bias the analyses by exclusion of extreme values. A non-parametric Kruskal-Wallis test, similar to an analysis of variance, was conducted to examine the effect of group on the onset asynchronies for each of the four temporal-order identification tasks. The effects of age group were statistically significant for all four temporal-order tasks (monaural two-item: Chi-square (2) = 102.1, $p < .001$; monaural four-item: Chi-square (2) = 26.3, $p < .001$; dichotic vowel identification: Chi-square (2) = 52.4, $p < .001$; dichotic ear identification: Chi-square (2) = 7.7, $p < .05$). Follow-up paired-comparison analyses were performed using the Mann-Whitney non-parametric test. When comparing the young to middle-aged groups, group differences in onset asynchrony were significant ($p < .01$) for all but the dichotic ear identification task ($p = 0.75$), with the middle-aged group performing more poorly. Comparing young to older adults, the older group had significantly ($p < .02$) longer stimulus onset asynchronies than the younger adults on all four tasks. Finally, the middle-aged group had significantly ($p < .03$) shorter onset asynchronies than the older adults for the two two-item vowel identification tasks (monaural and dichotic), but no significant ($p > .10$) differences were observed on the other two tasks.

C. Phase III: Temporal Masking of Vowel Identification

Recall that, in Phase III, forward and backward masking of vowel identification was measured for both a vowel-like pattern masker and a noise masker at predetermined masker-to-signal ratios. Figure 5 depicts the stimulus onset and offset asynchronies measured in each age group for the pattern masker, with forward masking conditions shown in the top two panels and backward masking conditions in the bottom two panels. The masker-to-signal ratios are indicated in the top right corner of each panel. Masker-to-signal ratio increases from left to right for both backward and forward masking and there is a trend in the data, based on visual inspection, for the stimulus onset or offset asynchronies to increase in all groups as the masker-to-signal ratio, or masker level, increases. This is as expected. Higher masker levels should lead to more temporal masking and this requires greater temporal separation between the maskers for the listener to correctly identify the vowel. Also, note that the top left and bottom right corners in Figure 5 depict data for the same masker-to-signal ratio (+4 dB). Visual comparison of these two panels reveals a slight trend toward the backward-masking condition yielding higher onset asynchronies than the forward masking condition. Finally, the horizontal dashed lines at 40 ms in each panel represent the asynchrony boundary between temporal + simultaneous masking (asynchronies less than 40 ms) and temporal masking only (asynchronies greater than 40 ms). Given the 40-ms duration of the vowel stimuli in these measurements, it is apparent in Figure 5 that a larger percentage of older adults needed physical separation between the target and masker (i.e.,

thresholds above the horizontal dashed line) to achieve the targeted identification performance level (61% correct).

An analysis of variance was performed on the data for each panel and demonstrated a significant ($p < .001$) effect of group in all four cases (backward masking, -2 dB: $F(2, 210) = 15.9$; backward masking, $+4$ dB: $F(2, 210) = 17.9$; forward masking, $+4$ dB: $F(2, 211) = 9.7$; forward masking, $+10$ dB: $F(2, 211) = 11.9$). Follow-up Bonferroni-adjusted t -tests revealed that it was the older group only that required significantly longer temporal separations between the pattern masker and the vowel to achieve the targeted identification performance (61% correct). For the two forward-masking conditions, the older group performed worse than the young group and, for the two backward-masking conditions, the older group performed worse than each of the other two age groups. No other group comparisons revealed significant differences.

Figure 6 displays data for the noise masker. Overall, in comparison to the data in Figure 5 for the pattern masker, visual inspection indicates the same overall pattern of results with generally less masking for the noise masker. An analysis of variance was performed to examine the effect of age group for each of the four temporal-masking measures for the noise masker. Significant ($p \leq .001$) effects of age group were obtained for all four conditions (backward masking, -2 dB: $F(2, 208) = 15.0$; backward masking, $+4$ dB: $F(2, 207) = 12.1$; forward masking, $+4$ dB: $F(2, 210) = 7.3$; forward masking, $+10$ dB: $F(2, 210) = 10.3$). Follow-up Bonferroni-adjusted t -tests revealed that it was the older group only that required significantly ($p < .05$) longer temporal separations between the pattern masker and the vowel to achieve the targeted identification performance (61% correct). For three of the four temporal-masking conditions, the older group performed worse than the young group only and, for one of the backward masking conditions (masker-to-signal ratio = -2 dB), the older group performed worse than each of the other two age groups. No other group comparisons revealed significant differences.

In the temporal-masking measurements of Phase III, the vowel duration was 40 ms compared to the 70 ms vowel duration used in the initial screening and Phase II. This longer duration was employed because preliminary pilot data suggested that too many elderly would not be able to do these initial tasks with a 40-ms vowel duration. Yet, 70-ms would be too long to expect significant amounts of temporal masking in Phase III. When deciding to use the shorter 40-ms vowel duration in the temporal-masking measures we also decided to measure vowel-identification in isolation for these shorter vowels. These RAU-transformed (Studebaker, 1985) percent-correct scores from the test ear were analyzed for group effects using an ANOVA. A significant effect of group was observed ($F(2, 212) = 3.5$, $p < .05$) and follow-up Bonferroni-adjusted t -tests indicated that the older adults had a significantly ($p < .05$) lower identification score in quiet for the 40-ms stimuli than the younger adults (a mean of 109.9 RAU for young adults versus a mean of 104.2 RAU for older adults). Thus, part of the reason older adults may have had more difficulty on the temporal-masking speech-identification tasks was because they also had more difficulty identifying the vowels in isolation, although only slightly more.

To examine the contributions of vowel identification performance in quiet to individual differences in the temporal masking of vowel identification, correlations were calculated between the vowel-identification score in quiet and the eight threshold stimulus onset or offset asynchronies measured. Correlations between these eight dependent measures and age were also examined. Vowel identification in quiet was negatively, weakly, but significantly correlated with each of the eight threshold onset/offset asynchronies ($-0.32 < r < -0.45$, $p < .001$). Age, on the other hand, was weakly, positively, but significantly correlated with each of the eight dependent measures ($0.30 < r < 0.40$, $p < .001$). Since the correlation

between age and vowel identification in quiet was significant ($r = -0.23$, $p < .001$), partial correlations were also examined, each controlling for the other variable in these analyses. In each case, the correlations between age or vowel-identification in quiet and each of the eight temporal-masking threshold asynchronies remained unchanged when controlling for the other variable. Thus, it appears that both age and vowel-identification performance in quiet have independent, significant, but relatively weak associations with temporal masking threshold asynchronies. Results indicated that the older the participant and the lower his or her vowel- identification performance in quiet, the greater the temporal masking.

D. Individual Differences among the Older Adults across Phases

A total of 124 older adults had completed all or most of the psychophysical measurements in Phases I, II and III. This was a sufficient sample size to enable examination of individual differences in performance across the 17 dependent measures included in this project. For the monaural 4-item vowel sequence identification measurements, however, about 20% of the participants could not do the task and had missing values. As a result, this dependent measure was eliminated from the analysis of individual differences. Missing values were scattered across various participants and tasks for the remaining dependent measures, with less than 5% of the data missing for 14 of these dependent measures and less than 10% for the remaining two dependent measures. In the analyses to follow, these remaining missing values were replaced with the group mean to yield a complete data set for 124 older adults.

Based on prior analyses of the data from Phase I and Phase II alone (Humes et al., 2009; Fogerty et al., 2009), it was anticipated that there would be some redundancy among the 16 dependent measures. To evaluate this here, two exploratory principal-components factor analyses (Gorsuch, 1983) were conducted. Both were based on analysis of the correlation matrix among the 16 dependent measures and used a factor selection criterion of eigen values > 1.0 , but one assumed orthogonal relationships among the ensuing factors (varimax rotation) and the other allowed the resulting factors to be correlated (Promax rotation, $\kappa = 4$). Given the presence of several moderate ($0.39 < r < 0.53$) correlations among the extracted components in the latter analysis, this analysis was adopted, the factor scores saved, and a subsequent orthogonal principal components analysis was conducted on this set of correlated factor scores.

The initial principal components analysis of the 16 dependent measures resulted in the identification of five components or factors accounting for a total of 72.6% of the variance. Communalities were good with all 16 values exceeding 0.54 and most exceeding 0.70. Table 3 shows the component weights of each of the 16 dependent variables for the pattern matrix that emerged from the initial oblique principal components analysis. Weights greater than 0.4 are in bold font to facilitate interpretation. Based on these component weights, each of the five factors or components was interpreted as follows: (1) two-item sequence identification and forward masking for the pattern masker; (2) temporal masking for the noise masker; (3) hearing threshold; (4) gap-detection threshold; and (5) dichotic two-item ear identification and backward masking for the pattern masker. The component correlation matrix revealed a correlation of 0.53 between the first two components, 0.44 between the first and the fifth components, and 0.39 between the second and fifth components. All other component correlations were less than 0.26. Thus, there were moderately strong associations among the measures from Phases II and III, but little association of these measures with those from Phase I. This was confirmed in the subsequent second-order principal components analysis, which accounted for 63.3% of the total variance with two orthogonal factors, one associated with factors 1, 2 and 5 from the first analysis (all Phase II and Phase III measures) and the other accounting for factors 3 and 4 from the initial analysis (all Phase I measures). Phase II and III measures all made use of brief vowels as stimuli and the task was always closed-set identification of the target vowel whereas Phase I measures made use

of non-speech tonal or noise stimuli and the tasks involved detection or discrimination rather than identification. As a result, it is not possible from these measures to determine if the common denominator underlying the second-order principal component structure is the stimulus (speech versus non-speech) or the task (identification versus detection/discrimination). Follow-up experiments of temporal order identification for non-speech sounds or gap-detection for speech stimuli would be needed to resolve this ambiguity. Nonetheless, regardless of the mechanism, there is considerable redundancy among the Phase II and III measures, but none between these measures and either measure from Phase I.

In an effort to identify factors contributing to the individual differences for each of the five principal components identified in the first analysis, five separate step-wise multiple regression analyses were performed, one for each factor score. The predictor variables examined included age and three factor scores from a principal components analysis of scores on the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III), derived for these same participants. The WAIS-III factor scores were interpreted as representing general cognitive processing, cognitive processing speed, and incidental learning. Thus, there were four predictors examined. Note that, given the foregoing factor analysis of the 16 dependent measures, there was no need to include hearing threshold or gap-detection threshold as potential predictors for Phase II or Phase III measures because these measures were ultimately found to be orthogonal or unrelated to one another. Finally, in each of the five step-wise multiple regression analyses, collinearity diagnostics revealed no significant collinearity among the set of predictor variables (high tolerance values, 0.74–0.96, and low non-significant partial correlations following each step).

For the first principal component, representing two-item temporal-order and forward masking for the pattern masker, the only significant predictor was the measure of general cognitive function from the WAIS-III. The adjusted R-squared value indicated that this predictor variable accounted for 21.7% of the total variance in this factor score. For the second principal component, representing temporal masking of vowel identification by the noise masker, age was the only predictor variable to emerge accounting for 10.4% of the variance. The same result was obtained for the third principal component, representing hearing threshold. Here, 13.9% of the variance was accounted for by age. For gap-detection measures, the fourth principal component, general cognitive function from the WAIS-III was the sole predictor and this accounted for 10.3% of the variance. Finally, for the fifth principal component, representing temporal-order ear identification and backward masking from the pattern masker, the sole predictor identified was the measure of cognitive processing speed from the WAIS-III, which accounted for 8.6% of the variance. Although each of the regression solutions was significant ($p < .05$), only from 8.6% to 21.7% of the variance could be accounted for by age or one of the three measures of cognitive function. Nonetheless, in each case, one of these variables was significantly related to individual differences in hearing sensitivity or temporal processing.

Discussion

This study examined differences in hearing threshold and temporal processing in young, middle-aged, and older adults, with relatively large samples for each age group. In general, the most common finding among the various group comparisons across tasks was that the older adults performed significantly worse than the young adults. In fact, these two groups differed significantly from one another on 16 of the 17 psychophysical measures included in this study; all but the gap-detection threshold at 1000 Hz. The performance of the middle-aged group also differed significantly from that of the young adults on several tasks. In particular, the middle-aged adults showed higher hearing thresholds than the young adults at

1414 and 4000 Hz, longer stimulus onset asynchronies for two-item monaural and dichotic temporal-order identification, and longer stimulus onset asynchrony for four-item temporal-order identification. No differences between young and middle-aged adults were seen in any of the eight temporal-masking conditions. On the other hand, the performance of the middle-aged adults was superior to that of the older adults on measures of hearing loss at 1414 and 4000 Hz, monaural and dichotic two-item temporal-order identification, and backward masking for the pattern (both masker-to-signal ratios) and noise (only the -2 dB masker-to-signal ratio) maskers.

Regarding the comparisons between the performance of young and older adults, the findings for hearing and gap-detection thresholds are generally consistent with previous findings in the literature, although the prior literature is more variable with regard to an effect of age group for the measures of gap-detection threshold (e.g., Moore *et al.*, 1992; Schneider *et al.*, 1994; Snell, 1997). Throughout this study, great care was taken to minimize the potential contributions of stimulus audibility on all measures of temporal processing. This was done by selecting high presentation levels and moderate bandwidths for the measures of gap detection and high presentation levels and low-pass filtering at 1800 Hz for the vowel stimuli. This issue of inaudibility was of greatest concern for the older adults, many of whom were likely to have significant high-frequency hearing loss. The success of this approach is probably most evident in the principal components analysis of the data from 124 older adults completing all three phase of this project. Here, hearing thresholds emerged as a factor separate from all other factors involving measures of temporal processing.

Grose, Hall & Buss (2006) measured gap-detection and gap-discrimination performance in middle-aged adults (40–55 y) and found significant deficits in this age group compared to young adults. Although this was not confirmed in this study for gap-detection thresholds, as noted, the middle-aged adults did perform significantly worse than young adults on several measures of temporal processing. Evidence in the group analysis and visual inspection of the scatterplots (Fig. 4) suggests that performance on the temporal order tasks gradually decreases across the full age range included here (18 to 89 y). This contrasts somewhat with performance for the temporal-masking tasks in which temporal thresholds remained relatively constant from young through middle-aged adults, then declined significantly for the older adults over 60 years of age.

The literature regarding age effects on many of the other measures of temporal processing obtained in this study, including temporal-order identification for brief vowels and temporal masking of vowel identification, is very sparse, even for comparisons between the two age groups at the ends of the continuum (young and older adults). The evidence provided in this study is that older adults have diminished ability to perform these temporal-processing tasks. In fact, even by middle age, average performance on several of these tasks is significantly worse than that of young adults.

Interestingly, among the 124 older adults completing all three phases, individual differences in gap-detection thresholds were not related to individual differences in the other measures of temporal processing or hearing sensitivity. This is most apparent in the principal components analysis which found gap-detection performance to be completely independent from all other measures of temporal processing in this study. As noted, this independence could be due to the difference in stimuli used, noise for gap detection and vowels for the other temporal processing tasks, the nature of the tasks, detection/discrimination for gap-detection thresholds and identification for the other temporal-processing tasks, or some other unknown cause. Additional research involving temporal-order identification for non-speech stimuli or gap-detection for speech stimuli would be needed to further elucidate the reasons underlying this lack of association.

Although hearing thresholds and gap-detection thresholds were not good predictors of individual differences in performance on the other measures of temporal processing, the multiple-regression analysis was able to identify at least one significant predictor variable for each of the five principal components that emerged from the psychophysical measures included in this study. The predictor that emerged in each case was either age or some aspect of cognitive function with about 10–20% of the variance accounted for in each case. Given the small amounts of variance accounted for in the regression analyses, there is still considerable room for improvement in identifying the factors underlying individual differences in temporal processing among older adults. As noted, this project includes parallel measures of temporal processing in vision and touch. Perhaps some of these measures will prove to be predictive of individual differences in auditory temporal processing among older adults, although an earlier analysis of the threshold sensitivity and gap-detection thresholds from Phase I failed to find much overlap across modalities (Humes et al., 2009). A more definitive answer regarding such overlap of temporal processing measures across modalities awaits completion of this ongoing project.

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References

- American National Standards Institute. Maximum permissible ambient noise levels for audiometric test rooms, ANSI S3.1–1999 (R2003). ANSI; Melville, NY: 2003.
- American National Standards Institute. Specification for audiometers, ANSI S3.6–2004. ANSI; Melville, NY: 2004.
- Boettcher F, Mills J, Swerdloff J, Holley B. Auditory evoked potentials in aged gerbils, responses elicited by noises separated by a silent gap. *Hear Res.* 1996; 102:167–178. [PubMed: 8951460]
- Cobb FE, Jacobson GP, Newman CW, Kretschmer LW, et al. Age-associated degeneration of backward masking task performance: Evidence of declining temporal resolution abilities in normal listeners. *Audiol.* 1993; 32:260–271.
- Cruikshanks, KJ.; Zhan, W.; Zhong, W. Epidemiology of age-related hearing impairment. In: Gordon-Salant, S.; Frisina, R.; Popper, A.; Fay, R., editors. *Springer Handbook for Auditory Research, Volume 33, The Aging Auditory System*. Springer; New York: in press
- Dorman MF, Kewley-Port D, Brady S, Turvey MT. Vowel recognition: Inferences from studies of forward and backward masking. *Quart J Exp Psychol.* 1977; 29:483–497.
- Fitzgibbons P, Gordon-Salant S. Auditory temporal order perception in younger and older adults. *J Speech Lang Hear Res.* 1998; 41:1052–1060. [PubMed: 9771628]
- Fitzgibbons PJ, Gordon-Salant S. Age effects on discrimination of timing in auditory sequences. *J Acoust Soc Am.* 2004; 116:1126–1134. [PubMed: 15376678]
- Fitzgibbons PJ, Gordon-Salant S. Effects of age and sequence presentation rate on temporal order recognition. *J Acoust Soc Am.* 2006; 120:991–999. [PubMed: 16938986]
- Fogerty D, Humes LE, Kewley-Port D. Auditory temporal-order processing of brief vowel sequences by young and elderly listeners. *J Acoust Soc Am.* 2009 (in press).
- Folstein MF, Folstein SE, McHugh PR. Mini-Mental State: A practical method for grading the cognitive state of patients for the clinician. *J Psychiatric Res.* 1975; 12:189–198.
- Frank T, Richards WD. Hearing aid coupler output level variability and coupler correction levels for insert earphones. *Ear Hear.* 1991; 12:221–227. [PubMed: 1916048]
- Gehr SE, Sommers MS. Age differences in backward masking. *J Acoust Soc Am.* 1999; 106:2793–2799. [PubMed: 10573894]
- Gorsuch, RL. *Factor Analysis. 2.* Lawrence Erlbaum Associates; Hillsdale, NJ: 1983.

- Grose JH, Hall JW III, Buss E. Temporal processing deficits in the pre-senescent auditory system. *J Acoust Soc Am*. 2006; 119:2305–2315. [PubMed: 16642844]
- Halling DC, Humes LE. Factors affecting the recognition of reverberant speech by elderly listeners. *J Speech Lang Hear Res*. 2000; 43:414–431. [PubMed: 10757693]
- He N, Horwitz AR, Dubno JR, Mills JH. Psychometric functions for gap detection in noise measured from young and aged subjects. *J Acoust Soc Am*. 1999; 106:966–978. [PubMed: 10462802]
- Humes L, Christopherson L. Speech identification difficulties of hearing-impaired elderly persons: The contributions of auditory processing deficits. *J Speech Hear Res*. 1991; 34:686–693. [PubMed: 2072694]
- Humes LE, Busey TA, Craig JC, Kewley-Port D. The effects of age on sensory thresholds and temporal gap detection in hearing, vision and touch. *Atten Perc Psychophys*. 2009; 71:860–871.
- ISO. ISO-7029, Acoustics-Statistical distribution of hearing thresholds as a function of age. International Standards Organization; Basel, Switzerland: 2000.
- Kawahara H, Masuda-Katsuse I, De-Cheveigne A. Restructuring speech representations using a pitch-adaptive time-frequency smoothing and an instantaneous-frequency-based F0 extraction: possible role of a repetitive structure in sounds. *Speech Comm*. 1999; 27:187–207.
- Levitt H. Transformed up-down method in psychoacoustics. *J Acoust Soc Am*. 1971; 49:467–477. [PubMed: 5541744]
- Moore BCI, Peters RW, Glasberg BR. Detection of temporal gaps in sinusoids by elderly subjects with and without hearing loss. *J Acoust Soc Am*. 1992; 92:1923–1932. [PubMed: 1401537]
- Newman CW, Spitzer JB. Prolonged auditory processing time in elderly: Evidence from a backward recognition-masking paradigm. *Audiol*. 1983; 22:241–252.
- Raz N, Millman D, Moberg PJ. Mechanism of age-related differences in frequency discrimination with backward masking: Speed of processing or stimulus persistence? *Psych. Aging*. 1990; 5:475–481.
- Salthouse, TA. A theory of cognitive aging. North-Holland; New York: 1985.
- Salthouse, TA. Steps toward the explanation of adult age differences in cognition. In: Perfect, TJ.; Maylor, EA., editors. *Models of cognitive aging*. Oxford University Press; New York: 2000. p. 19-49.
- Schneider BS, Hamstra SJ. Gap detection thresholds as a function of tonal duration for younger and older adults. *J Acoust Soc Am*. 1999; 106:371–380. [PubMed: 10420628]
- Schneider BS, Pichora-Fuller MK, Kowalchuk D, Lamb M. Gap detection and the precedence effect in young and old adults. *J Acoust Soc Am*. 1994; 95:980–991. [PubMed: 8132912]
- Shrivastav MN, Humes LE, Aylsworth L. Temporal-order discrimination of tonal sequences by younger and older adults: the role of duration and rate. *J Acoust Soc Am*. 2008; 124:462–471. [PubMed: 18646990]
- Snell KB. Age-related changes in temporal gap detection. *J Acoust Soc Am*. 1997; 101:2214–2220. [PubMed: 9104023]
- Snell KB, Frisina RD. Relationships among age-related differences in gap detection and word recognition. *J Acoust Soc Am*. 2000; 107:1615–1626. [PubMed: 10738815]
- Snell KB, Hu H. The effect of temporal placement on gap detectability. *J Acoust Soc Am*. 1999; 106:3571–3577. [PubMed: 10615697]
- Sommers M, Humes LE. Auditory filter shapes in the elderly: Effects of age and audibility. *J Acoust Soc Am*. 1993; 93:2903–2914. [PubMed: 8315154]
- Strouse A, Ashmead DH, Ohde RN, Grantham DW. Temporal processing in the aging auditory system. *J Acoust Soc Am*. 1998; 104:2385–2399. [PubMed: 10491702]
- Studebaker GA. A rationalized arcsine transform. *J Speech Hear Res*. 1985; 28:455–462. [PubMed: 4046587]
- Trainor LJ, Trehub SE. Aging and auditory temporal sequencing: Ordering the elements of repeating tone patterns. *Perc Psychophys*. 1989; 45:417–426.
- Verhaeghen P, De Meersman L. Aging and the negative priming effect: A meta-analysis. *Psych Aging*. 1998a; 13:1–9.
- Verhaeghen P, De Meersman L. Aging and the Stroop effect: A meta-analysis. *Psych Aging*. 1998b; 13:120–126.

- Walton J, Frisina R, O'Neill WE. Age-related alteration in processing temporal sound features in the auditory midbrain of the CBA mouse. *J Neurosci*. 1998; 18:2764–2776. [PubMed: 9502833]
- Walton J, Orlando M, Burkhard R. Auditory brainstem response forward-masking recovery functions in older humans with normal hearing. *Hear Res*. 1999; 127:86–94. [PubMed: 9925019]
- Wechsler, D. Wechsler Adult Intelligence Scale. 3. The Psychological Corporation; San Antonio, TX: 1997. (WAIS-III)
- Zwicker E, Schorn K. Temporal resolution in hard-of-hearing patients. *Audiol*. 1982; 21:474–492.

Figure 1.

(TOP) The temporal alignment of the 70-ms vowel stimuli used in the Phase-II temporal-order identification measures is depicted schematically in the top three rows of this figure. As noted, the vowel stimuli were in a /p/-vowel-/t/ context and the specific stimuli included in these illustrations are just one of several possible sequences presented to the listeners. The first and second rows are illustrations of the monaural (right ear) two-item and four-item sequences, respectively, whereas the third row illustrates the dichotic two-item sequences. For the dichotic stimuli, two different response tasks were used: vowel sequence identification (pet-pot would be the correct response in this case) and ear-sequence identification (right-left, or simply right, would be the correct response in this case). The temporal separation between onsets of successive stimuli in the sequence is the “stimulus onset asynchrony” and the separations shown in this schematic represent the mean values measured in the young adults. (BOTTOM) The temporal alignment of a 200-ms masker relative to the 40-ms vowel signals is shown in the bottom row. In the backward masking condition the vowel precedes the masker, while in the forward masking condition the vowel follows the masker. For backward-masking conditions, when the onsets of the masker and the target signal are aligned, there is no backward masking, only simultaneous masking. This is the minimum stimulus onset asynchrony (0 ms) permitted. Likewise, for forward-masking conditions, when the *offsets* of the masker and target signal are aligned, there is no forward masking, only simultaneous masking. This is the minimum stimulus offset asynchrony (0 ms) permitted. When the onset or offset asynchronies are between 0–40 ms, both temporal and simultaneous masking occur, and when the asynchronies exceed 40 ms, only temporal masking applies. In both the forward and backward-masking conditions, the signal was one of the four vowels in /p/-vowel-/t/ context, but 40-ms in duration for the Phase III temporal-masking measurements.

Figure 2. Scatterplots of hearing threshold in dB SPL as a function of participant age for pure-tone frequencies of 500 (top), 1414 (middle) and 4000 (top) Hz and for the young (circles), middle-aged (triangles) and older (squares) adults.

Figure 3.

Scatterplots of gap-detection thresholds in ms as a function of participant age for noise center frequencies of 1000 (top) and 3500 (bottom) Hz and for the young (circles), middle-aged (triangles) and older (squares) adults.

Figure 4.

Scatterplots of stimulus onset asynchronies in ms as a function of participant age for monaural two-item sequences (top left), monaural four-item sequences (top right), dichotic two-item vowel identification (bottom left) and dichotic two-item ear identification (bottom right) and for the young (circles), middle-aged (triangles) and older (squares) adults.

Pattern Masker

Figure 5. Scatterplots of stimulus onset or offset asynchronies in ms as a function of participant age for forward masking (top) and backward masking (bottom). Masker-to-signal amplitude ratios in dB are shown in each panel and increase from left to right. Data for the pattern masker are shown for the young (circles), middle-aged (triangles) and older (squares) adults.

Figure 6. Scatterplots of stimulus onset or offset asynchronies in ms as a function of participant age for forward masking (top) and backward masking (bottom). Masker-to-signal amplitude ratios in dB are shown in each panel and increase from left to right. Data for the noise masker are shown for the young (circles), middle-aged (triangles) and older (squares) adults.

Table 1

Numbers of young, middle-aged, and older adults included in the Phase I, II and III datasets in this report and those from each age group and phase who comprised datasets in prior publications from this project.

Study Phase	Age Group	Sample Size (N)	Prior Sample Size
I	Young	122	42
	Middle-aged	45	0
	Older	172	137
	Total	339	179 [*]
II	Young	76	35
	Middle-aged	32	0
	Older	157	151
	Total	265	186 ^{**}
III	Young	62	0
	Middle-aged	24	0
	Older	129	0
	Total	215	0

* Previously published in Humes et al. (2009).

** Previously published in Fogerty et al. (in press).

Pearson-r correlations between age and each of the five dependent measures from Phase I. GDT = gap-detection threshold. All correlation coefficients were statistically significant ($p < .01$).

Table 2

	Threshold 500 Hz	Threshold 1414 Hz	Threshold 4000 Hz	GDT 1000 Hz	GDT 3500 Hz
Age	.56	.59	.77	.15	.26
Threshold 500 Hz		.73	.57	.24	.30
Threshold 1414 Hz			.69	.27	.38
Threshold 4000 Hz				.21	.34
GDT 1000 Hz					.75

Table 3

Component weights in the pattern matrix of the oblique principal-components for the 16 dependent measures completed by 124 older adults in this study.
PC= Principal Component; GDT= gap-detection threshold.

Variable	PC1	PC2	PC3	PC4	PC5
GDT 1000	.11	.08	.02	.87	.01
GDT 3500	.10	.01	.12	.84	.12
Thresh 500	.16	-.07	.64	.16	-.28
Thresh 1414	-.03	.12	.86	.05	-.11
Thresh 4000	-.17	.05	.74	-.01	.20
Mono 2	.78	-.13	.13	.05	.06
Dich 2 ID	.54	.05	-.05	.05	.29
Dich 2 LOC	-.15	.05	-.30	.32	.77
FM Patt +4	.96	-.11	-.05	.12	-.05
FM Patt +10	.90	-.03	-.03	.17	.00
FM Noise +4	.50	.51	-.10	-.17	-.08
FM Noise +10	.66	.38	-.14	-.12	-.08
BM Patt -2	.17	.01	.29	-.18	.60
BM Patt +4	.41	-.03	.06	-.16	.63
BM Noise -2	-.10	.94	.08	.07	.02
BM Noise +4	-.05	.92	.08	.10	.05