HHS Public Access

Author manuscript

Hear Res. Author manuscript; available in PMC 2022 April 01.

Published in final edited form as:

Hear Res. 2021 April ; 403: 108188. doi:10.1016/j.heares.2021.108188.

Peripheral deficits and phase-locking declines in aging adults

Samira Anderson[*], **Rebecca Bieber**, **Alanna Schloss**

Department of Hearing and Speech Sciences, University of Maryland, College Park, MD 20742

Abstract

Age-related difficulties in speech understanding may arise from a decrease in the neural representation of speech sounds. A loss of outer hair cells or decrease in auditory nerve fibers may lead to a loss of temporal precision that can affect speech clarity. This study's purpose was to evaluate the peripheral contributors to phase-locking strength, a measure of temporal precision, in recordings to a sustained vowel in 30 younger and 30 older listeners with normal to near normal audiometric thresholds. Thresholds were obtained for pure tones and distortion-product otoacoustic emissions (DPOAEs). Auditory brainstem responses (ABRs) were recorded in quiet and in three levels of continuous white noise (+30, +20, and +10 dB SNR). Absolute amplitudes and latencies of Wave I in quiet and of Wave V across presentation conditions, in addition to the slope of Wave V amplitude and latency changes in noise, were calculated from these recordings. Frequency-following responses (FFRs) were recorded to synthesized /ba/ syllables of two durations, 170 and 260 ms, to determine whether age-related phase-locking deficits are more pronounced for stimuli that are sustained for longer durations. Phase locking was calculated for the early and late regions of the steady-state vowel for both syllables. Group differences were found for nearly every measure except for the slopes of Wave V latency and amplitude changes in noise. We found that outer hair cell function (DPOAEs) contributed to the variance in phase locking. However, the ABR and FFR differences were present after covarying for DPOAEs, suggesting the existence of temporal processing deficits in older listeners that are somewhat independent of outer hair cell function.

Keywords

Auditory Aging; Phase locking; Auditory brainstem response; Frequency-following response; Peripheral deficit

Introduction

Most older adults report some degree of hearing decline, especially when the clarity of the speech signal is degraded by competing noise, rapid speaking rate, or unfamiliar accent or

[*]Corresponding author. Samira Anderson: sander22@umd.edu.

COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflicts of interests.

dialect. These difficulties can occur in individuals with normal audiometric thresholds. Speech understanding difficulties have been attributed to varying degrees of loss in peripheral, central, and cognitive systems (CHABA, 1988). Age-related deficits in the neural representation of speech and non-speech stimuli have been demonstrated across multiple studies (Anderson et al., 2012; Billings et al., 2015; Eddins and Eddins, 2018; Gaskins et al., 2019; Goossens et al., 2016; Mamo et al., 2016; Presacco et al., 2016; Roque et al., 2019a; Roque et al., 2019b; Vercammen et al., 2018), but the mechanisms for these observed neural changes are not yet fully understood. It has been suggested that decreased afferent input and degraded auditory nerve function may lead to cascading changes throughout the auditory system (Cai et al., 2018; Chambers et al., 2016; Parthasarathy and Kujawa, 2018; Torre and Fowler, 2000; Wang et al., 2011). For example, a loss of auditory nerve fibers may lead to reductions in phase-locking strength, especially for responses to sustained components of auditory stimuli. This study's purpose was to determine the contributions of peripheral auditory function to reductions in phase-locking strength in younger and older listeners with normal to near normal hearing thresholds, using audiometric testing, distortion-product otoacoustic emissions (DPOAEs) measurement, and auditory brainstem response (ABR) testing.

Age-related disruptions in phase locking

The assessment of phase locking provides an indirect measure of neural synchrony by quantifying the consistency of trial-to-trial representation of the stimulus phase. As reductions in neural synchrony may reduce fidelity of the auditory signal, one consequence of an age-related reduction in phase locking may be difficulty understanding speech, especially in noise (McClaskey et al., 2019). Both human and animal studies have demonstrated age-related reductions in phase locking to non-speech and speech stimuli (Anderson et al., 2012; Hao et al., 2018; Harris and Dubno, 2017; Overton and Recanzone, 2016; Parthasarathy et al., 2014; Roque et al., 2019a; Roque et al., 2019b). Further exploration of the factors that contribute to phase-locking strength may lead to a better understanding of the difficulties older listeners experience when listening to speech in noise.

Phase locking may be more susceptible to age-related degradation for sustained stimuli that place a strain on neural refraction (Walton et al., 1998). A prior study examined frequency-following responses (FFRs) to a synthesized vowel (/a/) and a synthesized consonant-vowel syllable (/da/) (Presacco et al., 2015). The vowel durations in these stimuli differed: the /da/ had a shorter sustained vowel duration of 110 ms compared to the /a/ vowel duration of 170 ms. This study found that older normal-hearing (ONH) listeners demonstrated an abrupt decrease in phase locking strength in the later region (after ~110 ms) of the /a/, whereas a similar drop was not observed in the responses of young normal-hearing (YNH) listeners. In contrast, a drop in phase locking was not noted in either group of listeners in any region of the /da/ syllable. Potential mechanisms for this age-related reduction in phase locking to a sustained stimulus include a reduction in auditory nerve fibers (Schmiedt et al., 1996; Wu et al., 2019), cochlear synaptopathy (Sergeyenko et al., 2013; Viana et al., 2015), or other sources of neural degradation. The convergence of auditory nerve fibers onto targets in the cochlear nucleus appears to contribute to the robustness of phase locking (Joris and Smith, 2008), and therefore a reduction in these fibers may affect FFRs to a sustained stimulus.

In order to clarify the source of the age-related drop in sustained phase-locking, the current experiment extended the findings of Presacco et al. (2015) in several ways. Several measurements of peripheral auditory function were performed to determine potential contributors to decreased phase locking, including audiometry that included extended high frequencies in addition to the conventional audiometric range, distortion-product otoacoustic emissions, and auditory brainstem responses recorded in quiet and in three levels of noise. Additionally, in the Presacco et al. study, the /da/ and /a/ stimuli differed in initial frequency content, with the /da/ stimulus having a higher second formant onset frequency (1700 Hz) than the second formant frequency of the /a/ vowel (1240 Hz). To ensure that these stimulus differences did not influence the results, we opted to repeat the experiment with two consonant-vowel syllables that differed only in the duration of the vowel, a 170-ms /ba/ (vowel duration 110 ms) and a 260-ms /ba/ (vowel duration 200 ms). The second formant onset frequency of these stimuli was 900 Hz.

Age-related threshold changes

Conventional audiometry includes frequencies from 250 to 8000 Hz, based on the assumption that this frequency range adequately represents the range of frequencies most important for understanding speech (Stevens, 1998). However, high-frequency (HF) consonants such as /s/ and /ʃ/ have energy that can extend up to 10 kHz in individual female speakers (Boothroyd and Medwetsky, 1992; Boothroyd et al., 1994). Older adults who have normal audiometric thresholds through 8000 Hz almost always experience a loss of hearing sensitivity above 8000 Hz, and this change starts to occur in middle age (40 to 59 years) (Jilek et al., 2014; Stelmachowicz et al., 1989). A large-scale study of 122 middle-aged adults (ages 30–47) found that extended high-frequency thresholds, along with working memory, accounted for 41% of the variance in a composite speech-in-noise score that combined self-assessment and behavioral measures (Yeend et al., 2019). Even younger adults can have hearing loss in the extended HF range, and this hearing loss correlates with self-reported hearing difficulties in noise (Motlagh Zadeh et al., 2019). Overall, these results suggest that thresholds in the HF range above 8000 Hz may contribute to the speech understanding difficulties observed in older adults.

Otoacoustic emissions (OAE) testing may be more sensitive to outer hair cell loss than audiometric threshold testing (Fabijańska et al., 2012). Adults over age 65 demonstrate substantial loss of OAE amplitude, even for lower frequencies at which audiometric thresholds are relatively unimpaired (Abdala and Dhar, 2012; Uchida et al., 2008). Therefore, OAEs may serve as an early indicator of changes in cochlear function. Decreased OAE amplitude may be a factor in speech-in-noise performance, but the evidence is mixed. A study of 53 listeners ranging in ages from 22–71 found a significant relationship between outer hair cell function and speech-in-noise performance (Hoben et al. 2017). However, in a larger study of 194 young adults (18–30 yrs), high-frequency hearing thresholds, DPOAEs, and Wave I amplitude of the auditory brainstem response did not predict performance on the Quick Speech-in-Noise test (Smith et al., 2019). It is possible that peripheral deficits play a more important role in speech-in-noise performance in older adults, who are more likely to experience early subclinical changes in auditory nerve function.

Cochlear synaptopathy

Cochlear synaptopathy or a loss of auditory nerve fibers may be present in the absence of elevated audiometric thresholds or outer hair cell loss. Animal models have suggested that noise exposure that is insufficient to produce permanent hearing threshold shift may result in a disruption of synapses between cochlear hair cells and auditory nerve fibers (Kujawa and Liberman, 2009; Lin et al., 2011). Wave I of the auditory brainstem response (ABR) arises from the distal end of the auditory nerve (Jewett and Williston, 1971), and has been proposed as a putative measure of cochlear synaptopathy as its amplitude correlates with spiral ganglion cell counts (Kujawa and Liberman, 2009; Parthasarathy and Kujawa, 2018). However, the evidence for noise-induced cochlear synaptopathy in humans is mixed, and studies using a variety of metrics (electrophysiology, questionnaires, and behavioral measures) have failed to provide conclusive evidence that noise is a contributor to synaptopathy (as reviewed in Bramhall et al., 2019).

Aging may be a more significant factor in synaptopathy than noise exposure, and human temporal bone studies have provided evidence of age-related synaptopathy (Makary et al., 2011; Viana et al., 2015; Wu et al., 2019). In addition, Sergeyenko et al. (2013) noted age-related synaptopathy in quiet-reared CBA mice. The CBA mice provide an appropriate model to evaluate aging effects, as their hearing is preserved until they are advanced in age (Frisina et al., 2011). Although numerous studies have investigated possible measures of noise-related synaptopathy in young adults, few studies have investigated correlates of age-related synaptopathy in living humans. A recent study conducted by Grose et al. (2019) showed that older adults with near-normal hearing thresholds had significantly reduced ABR Wave I amplitudes and Wave I to V ratios compared to younger adults. They also compared amplitude modulation detection and spectral modulation detection thresholds between younger and older adults, hypothesizing that a loss of low-spontaneous rate auditory nerve fibers associated with synaptopathy would lead to a reduction in processing fidelity. They did not find any group differences, however, and concluded that cochlear synaptopathy cannot be demonstrated by testing spectral and temporal modulation detection thresholds, at least using the paradigms employed in their particular study.

The addition of masking noise to the ABR recording may tax the auditory system and reveal deficits that might not otherwise be revealed when the stimulus is presented in quiet. The slope of noise-induced shifts in Wave V latency has been suggested as a proxy for cochlear synaptopathy (Mehraei et al., 2016). One reason for the selection of Wave V latency as the primary variable of interest in the Mehraei et al. study was the assumption that Wave I amplitude is not a robust clinical measure, although it can be a stable measure under certain conditions (Bieber et al., 2020; Guest et al., 2019). Mehraei et al. found that the slope of noise-induced latency shift was related to a measure of temporal processing – the envelope interaural timing difference threshold. We therefore adopted this measure – slope of noise-induced latency shifts - to assess peripheral dysfunction and its contributions to phase-locking deficits in older compared to younger listeners.

We note that a recent study found that test-retest reliability of “ABR difference measures” (e.g., Wave V latency shift in noise and Wave I amplitude increase with level) was moderate to poor [intra-class correlation coefficients (ICCs) of 0.45 and 0.52, respectively], whereas

the absolute latency and amplitude ABR measures had good test-retest reliability (ICCs: 0.85–0.86) in a sample of young listeners (Guest et al., 2019). The authors did not find any correlations among the ABR measures and middle-ear muscle reflex and envelope following-response measures (previously proposed as proxy measures of synaptopathy) and suggested that measures be regarded with caution for use in diagnosis of synaptopathy in young adults. Because of the Guest at al. findings, we chose to calculate absolute Wave I and V amplitudes and Wave V latencies, in addition to the Wave V latency and amplitude shifts in noise to increase our ability to detect age-related synaptopathy.

We used ABR and FFR recordings in conjunction with audiometric and DPOAE testing to test the following hypotheses: 1) measures of peripheral auditory function will contribute to variance in sustained phase locking in older listeners, 2) slopes of Wave V latency and amplitude noise-induced shifts will be shallower in older vs. younger listeners, and 3) the age-related reduction in phase locking will be greater for the 260-ms /ba/ than the 170-ms /ba/.

METHOD

Participants

Older normal-hearing (ONH) listeners [n=30 (8 males), ages 55–70 (mean=63.83, s.d.=5.31)] and younger normal-hearing (YNH) listeners [n=30 (6 males), ages 18–25 (mean=21.01, s.d.=1.55)] were recruited to participate in the study via advertisements in local newspapers and flyers that target seniors. The groups did not differ significantly in sex distribution ($^2 = 0.37$, $p = 0.76$). Inclusion criteria included audiometric thresholds ≤ 20 dB HL from 125–4000 Hz and ≤ 30 dB HL from 6000–8000 Hz and no interaural symmetries ≥ 15 dB HL at two or more consecutive frequencies. Audiometric threshold testing was also conducted for the extended high-frequency range (9000–14,000 Hz), but these thresholds were not included as qualification criteria. Additionally, participants all had normal cognitive function as demonstrated by scores ≥ 26 on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) and IQ ≥ 85 on the Wechsler Abbreviated Scale of Intelligence (WASI; Zhu and Garcia, 1999). Exclusion criteria included history of middle ear surgery and diagnosis of neurological impairment. Participants were compensated for their time. The study was approved by the Institutional Review Board of the University of Maryland.

Threshold testing

Audiometric Thresholds—Using the Modified Hughson-Westlake procedure (Carhart and Jerger, 1959), air-conduction thresholds from 1.25–8 kHz were obtained with insert 3A earphones (Etymotic Research, Elk Grove Village, IL) and from 9–14 kHz with Sennheiser HDA 300 circumaural headphones (Lyme, CT). The stimuli were presented through an Interacoustics A440 audiometer (Eden Prairie, MN).

Distortion-Product Otoacoustic Emissions (DPOAEs)—DPOAEs were measured with L1 and L2 levels of 65 and 55 dB SPL, respectively, from 1 kHz to 14 kHz at 2.0 frequencies/octave in the right and left ears using the Intelligent Hearing Systems

SmartOAE system (IHS, Miami, FL). Prior to each recording, in-ear calibration coupled to a 10D OAE probe was performed using IHS SmartOAE software. Input-output functions were also obtained in the right ear starting with L1 and L2 levels of 25 and 15 dB SPL, respectively, and increasing until maximum levels of 85 and 75 dB SPL, respectively, were reached. Thresholds, defined as the minimum L1 required to achieve a signal-to-noise (SNR) ratio ≥ 6 dB and absolute level of > 0 dB SPL, were obtained for 16 F2 frequencies from 1105 Hz – 7450 Hz. We tested frequencies above 7450 Hz but noted problems with standing wave interference in many of our participants and did not include these frequencies in the analysis. We created an average DPOAE threshold (DPAVG) that included frequencies from 2211–7427 Hz to use in our analysis of factors contributing to phase-locking strength. We did not choose to use the DP amplitudes or SNRs at the 65 and 55 dB SPL presentation levels, because we noted that 16 of the 30 participants (15 ONH) did not meet the criteria of SNR ratio ≥ 6 dB and absolute level of > 0 dB SPL with these presentation levels at all frequencies.

Auditory Brainstem Response (ABR)

ABRs were recorded to a 100-μs broadband click stimulus presented to the right and left ears at a rate of 21.1 Hz and a level of 80 dB SPL through electromagnetically shielded ER-3A insert earphones using the IHS SmartEP system. The recording software employed a sampling rate of 10 kHz and on-line filtering of 50–3000 Hz. In addition to the quiet presentations, the click stimulus was also presented in ipsilateral white noise at +10, +20, and +30 dB SNR. A two-channel vertical electrode montage was employed (Cz: active; earlobes: reference; forehead: ground). Absolute and inter-electrode impedances were ≤ 3 kΩ. A minimum of two replicable recordings of 2000 sweeps were obtained for each condition.

An automated algorithm was performed in MATLAB (MathWorks, version 2012a) to extract peak amplitudes and latencies for Waves I and V. The Wave V latencies were extracted from the vertical montage (Cz active, earlobe reference) for the quiet and noise conditions. The slopes of the Wave V latency and amplitude shifts in noise were computed by best linear fit across the four quiet and noise conditions. Wave I amplitude was calculated using a derived horizontal montage (right earlobe reference, left earlobe active) to maximize amplitude.

Frequency-following response (FFR)

Stimuli.: The syllable /ba/ was generated in Praat at a 20-kHz sampling rate using a Klatt-based synthesizer (Boersma and Weenink, 2009) with two durations, 170 ms and 260 ms. Both syllables contained a voicing onset at 10 ms and a 50-ms transition from the consonant to the vowel. The duration of the vowel was 110 ms and 200 ms for the shorter and longer syllable durations, respectively. The fundamental frequency (F_0) was 100 Hz throughout the duration of the syllable. During the consonant transition, the first formant shifted from 400 to 720 Hz, the second formant shifted from 900 to 1240 Hz, and the third formant shifted from 2580 to 2500 Hz. Formants four through six were steady for the duration of the syllables (3300 Hz, 3750 Hz, and 4900 Hz, respectively).

Recording.: The stimuli were presented monaurally to the right ear via Presentation software (Neurobehavioral Systems, Berkeley, CA) at rates of 4 Hz and 3 Hz for the 170-ms and 260-ms /ba/ stimuli, respectively, through insert earphones (ER1, Etymotic Research, Elk Grove Village, IL). A standard vertical montage of five electrodes was used (Cz active, two forehead ground common mode sense/driven right leg electrodes, and earlobe references). Responses were recorded using the Biosemi ActiABR-200 acquisition system (Biosemi B.V., Amsterdam, Netherlands) at a sampling frequency of 16,384 Hz and an online bandpass filter of 100 to 3000 Hz. A minimum of 3300 artifact-free sweeps were recorded for each syllable from each participant.

Data reduction.: Data were analyzed in MATLAB (version R2011b; MathWorks, Natick, MA) and were converted into MATLAB format using the pop_biosig function from EEGLab (Delorme and Makeig, 2004). The artifact reject criterion was set at ± 30 μV. Responses were filtered offline from 70–2000 Hz using a zero-phase 4^{th} order Butterworth filter and averaged over 250-ms and 340-ms windows for the 170-ms and 260-ms durations, respectively.

Data analysis.: Phase-locking factor (PLF) was calculated using a procedure identical to that described in previous studies (Jenkins et al., 2018; Roque et al., 2019a; Roque et al., 2019b). Morlet wavelets (Tallon-Baudry et al., 1996) were used to decompose the signal from 80 to 800 Hz and calculate PLF values for the 100-Hz F_0 for the early and late vowel regions for the two syllables: 60–120 m and 160–240 ms for the 240-ms /ba/ and 60–120 ms and 120–180 ms for the 170-ms /ba/.

Statistical Analysis

The statistical analyses were completed in JASP (JASP Team, 2018). Split-plot analyses of variance (ANOVA) were conducted to assess between-group differences (YNH vs. ONH) in hearing thresholds and within group differences in frequencies tested with the audiogram and with DPOAEs. Analyses of covariance (ANCOVAs) were used to compare listener groups on the following variables: ABR Wave I amplitude and latency, Wave V/I ratio, and slopes of Wave V latency and amplitude shifts in noise. Split-plot ANCOVA were conducted to assess between-group differences (YNH vs. ONH), and within-group effects of noise (4 levels: quiet and 3 SNR conditions) for Wave V latency and amplitude. Split-plot ANOVAs were completed for evaluating between-group comparisons (YNH vs. ONH), and within-group effects of stimulus (long /ba/ vs. short /ba/) and stimulus region (early vs. late vowel) on the FFR PLF. A multiple linear regression was performed with the PLF corresponding to the late vowel region of the long /ba/ syllable serving as the dependent variable and DPAVG, ABR Wave I amplitude, sex, and the DPOAE × Wave I interaction serving as independent variables. The appropriateness of the linear regression analysis for the data set was verified by checking the residuals for normality. Pearson's correlations were used to calculate relationships among the variables included in the linear regression. The false discovery rate method was used to control for multiple comparisons (Benjamini and Hochberg, 1995).

RESULTS

Audiometric Thresholds

Despite relatively strict criteria for enrollment in the study, the ONH listeners had elevated pure-tone thresholds compared to the YNH listeners [$F_{(1,58)} = 402.9$, $p < 0.001$, $\eta^2 = 0.87$]. These threshold elevations were present at every frequency tested (Fig. 1). As expected, there was a significant frequency × group interaction [$F_{(11,638)} = 153.7$, $p < 0.001$, $\eta^2 = 0.51$], such that the group threshold differences widened as frequency increased above 3 kHz.

Distortion-Product Otoacoustic Emissions

Mirroring the pure-tone audiometry results, the ONH listeners had elevated DPOAE thresholds compared to YNH listeners at every frequency [$F_{(1,46)} = 27.0$, $p < 0.001$, $\eta^2 = 0.37$] (Fig. 1). There was also a significant frequency × group interaction [$F_{(8,368)} = 2.72$, $p = 0.019$, $\eta^2 = 0.04$. Greenhouse-Geisser correction], such that the group threshold differences widened as frequency increased above 2.6 kHz.

ABR Wave I

Usable recordings for Wave I identification were obtained in 29/30 YNH listeners and in 25/30 ONH listeners. Three recordings (1 YNH and 2 ONH) were eliminated due to tester error. Four recordings (4 ONH) were eliminated due to excessive noise which precluded peak identification. Figure 2 displays group average waveforms from the derived horizontal montage to emphasize the Wave I component. Box plots show Wave I amplitude, Wave V/I ratio, and Wave I latency values. To reduce the influence of cochlear hearing loss, we performed separate analyses of covariance (ANCOVA) for Wave I amplitude, Wave V/I ratio, and Wave I latency and covaried for DPAVG. Results of the ANCOVA showed that the YNH listeners had larger Wave I amplitudes than the ONH listeners [$F_{(1,51)} = 7.63$, $p = 0.008$, $\eta^2 = 0.13$], but there were no group differences for the Wave V/I ratio [$F_{(1,51)} = 1.03$, $p = 0.32$, $\eta^2 = 0.02$] or Wave I latency [$F_{(1,49)} = 0.01$, $p = 0.94$, $\eta^2 = 0.00$].

ABR Wave V

Usable recordings for Wave V identification were obtained in 29/30 YNH listeners and in 27/30 ONH listeners. One recording (1 YNH) was eliminated due to tester error. Four recordings (4 ONH) were eliminated due to excessive noise which precluded peak identification. Figure 3 displays group average waveforms from the ipsilateral vertical montage. Split-plot ANCOVAs were conducted for latency and amplitude across the four presentation SNR conditions (quiet and three SNRs), covarying for DPAVG. Compared to YNH listeners, ONH listeners had significantly longer Wave V latencies across conditions [$F_{(1,53)} = 5.36$, $p = 0.03$, $\eta^2 = 0.09$]. The effect of SNR was not significant [$F_{(3,159)} = 2.47$, $p = 0.06$, $\eta^2 = 0.04$], and the group × SNR interaction was not significant [$F_{(3,159)} = 0.62$, $p = 0.60$, $\eta^2 = 0.01$].

Compared to YNH listeners, ONH listeners had significantly smaller Wave V amplitudes across conditions [$F_{(1,53)} = 15.39$, $p < 0.001$, $\eta^2 = 0.22$]. The effect of SNR on amplitude did not meet statistical significance [$F_{(3,140)} = 1.12$, $p = 0.32$, $\eta^2 = 0.02$, Greenhouse-Geisser],

and there was no significant group × SNR interaction [$F_{(3,140)} = 1.17$, $p = 0.32$, $\eta^2 = 0.02$, Greenhouse-Geisser]. To determine if synaptopathy or a loss of auditory nerve fibers was a factor in the results, we performed an additional analysis and covaried for Wave I amplitude. The aging effects persisted for Wave V latency [$F_{(1, 51)} = 5.40$, $p = 0.02$, $\eta^2 = 0.08$] and amplitude [$F_{(1, 51)} = 9.67$, $p = 0.003$, $\eta^2 = 0.15$].

Figure 4 displays the group averages overlaid by SNR and box plots displaying average slopes for latency and amplitude. Neither the latency slope nor the amplitude slope were statistically different between YNH and ONH listeners [latency slope: $F_{1,53)} = 0.73$, $p = 0.40$, $\eta^2 = 0.01$; $F_{1,53)} = 2.96$, $p = 0.09$, $\eta^2 = 0.05$].

FFR

Figure 5 displays the stimulus spectra of the short and long /ba/ syllables and corresponding group average waveforms. A decrease in response amplitude for the older adults is evident for both the short and long syllables. Figure 6 compares average phase locking to the temporal envelope of the short and long /ba/ in YNH and ONH listeners. Visual examination of the figures reveals age-related reductions in phase locking to the F_0 for both the /ba/ syllables, and a split-plot ANOVA confirmed a main effect of group [$F_{(1,58)} = 14.05$, $p < 0.001$, $\eta^2 = 0.20$]. There was also an effect of syllable duration, such that overall phase locking was higher for the long /ba/ than for the short /ba/ [$F_{(1,58)} = 4.75$, $p = 0.033$, $\eta^2 = 0.07$]. There was a region × group interaction [$F_{(1,58)} = 7.93$, $p = 0.009$, $\eta^2 = 0.11$] that was driven by a decrease in phase locking from the early to late regions of the vowels in the ONH listeners ($p = 0.004$) that was not found in the YNH listeners ($p = 0.47$). None of the other interactions were significant (all p values > 0.05).

Peripheral-Midbrain Relationships

A multiple linear regression was conducted to identify the potential factors that contribute to strength of phase locking, with the PLF to the second region of the longer /ba/ syllable serving as the dependent variable. Independent variables were chosen to represent outer hair cell function (DPAVG) and auditory nerve function/afferent function (Wave I amplitude). Sex was also included as independent variable due to known sex effects on FFR and ABR amplitudes (Bramhall et al., 2017; Jerger and Hall, 1980; Krizman et al., 2012; Mitchell et al., 1989; Prabhu et al., 2016). Because afferent function may interact with outer hair cell function, we included the interaction between DPAVG and Wave I variables (Bramhall et al., 2015). The independent variables showed normal distributions (Shapiro-Wilk, all p values > 0.05), but a log-transform was necessary to normalize the distribution of the PLF. The stepwise model of entry was used. Collinearity diagnostics revealed satisfactory variance inflation factor (highest = 1.16) and tolerance (lowest = 0.86) values, ruling out strong correlations between predictor variables. One significant regression equation was returned. DPAVG significantly contributed to PLF variance [$F_{(1,51)} = 7.91$, $p = 0.007$], with an R^2 value of 0.14. The other variables did not make significant contributions. This model is summarized in Table 1. Pearson's correlations were also conducted among these variables and are displayed in Figure 7.

DISCUSSION

The purpose of this study was to investigate the factors that may contribute to reductions in phase locking to sustained stimuli in normal-hearing older listeners. To accomplish this objective, we compared phase locking to short and long duration /ba/ stimuli in YNH and ONH listeners, and we assessed hearing thresholds, outer hair cell function, (DPOAEs), auditory nerve function (Wave I), and brainstem function (Wave V recorded in quiet and noise conditions). The data support some but not all of our original hypotheses; in particular, 1) Wave I amplitudes were lower in ONH vs. YNH listeners (Fig. 2), and 2) Wave V latencies were delayed in ONH vs. YNH listeners (Fig. 3). Further, the data supported our hypothesis that peripheral factors would contribute to variance in phase locking (Table 1), but outer hair cell function was the only factor that explained significant variance in our stepwise model. We had hypothesized that slopes of Wave V latency and amplitude noise-induced shifts would be shallower in older vs. younger listeners, but the slopes were not statistically different between the groups (Fig. 4). Finally, we had hypothesized that age-related phase locking declines would be greater for the longer /ba/ than the shorter /ba/, but the group differences were similar for both syllables.

Auditory Brainstem Response

Latency prolongations and amplitude reductions across conditions were noted in ONH compared to YNH listeners. These results are consistent with previous aging ABR studies (Boettcher et al., 1993; Burkard and Sims, 2001; Jerger and Hall, 1980; Konrad-Martin et al., 2012; Skoe et al., 2015), but most of these studies were confounded by peripheral hearing loss, particularly at frequencies above 4 kHz. Boettcher et al. (1993) found an age-related reduction in ABR amplitudes in Mongolian gerbils, even when limiting the comparison between age groups to the older gerbils with lower ABR thresholds. In contrast, another study showed age-related changes in ABR latencies and amplitudes only in C57 mice, who show accelerated presbycusis, and not in the CBA normal-hearing mice (Willott, 1991). Furthermore, previous studies have shown that peripheral factors contribute to ABR abnormalities. In older rhesus monkeys, reduced DPOAE amplitudes contribute to delayed ABR latencies (Torre and Fowler, 2000), and in older rats, a greater loss of cochlear ribbon synapses is related to lower ABR amplitudes, especially for the earlier peaks (Cai et al., 2018). The aging effects in this study were present after covarying for DPAVG, a measure of outer hair cell function, and Wave I amplitude. Therefore, it appears that the aging effects on Wave V latencies and amplitudes are relatively independent of loss of outer hair cell function and auditory nerve fibers. In addition, the age-related reduction in Wave I amplitude appears to be independent of outer hair cell function. However, we acknowledge that we cannot rule out the possibility that peripheral deficits in the extended high frequencies were significant factors in the aging effects on the ABR, especially as the click ABR is dominated by the high-frequency components of the stimulus (Dau, 2003).

We did not find the expected effects of aging on the slopes of Wave V latency or amplitude with decreasing SNR. Furthermore, these slope measures were not related to Wave I amplitude. Our study differed from that of Mehraei et al. (2016) in a number of ways that may account for differing results concerning slope. First, we used 4 presentation conditions

and Mehraei et al. used 5 conditions; more data points may have resulted in a more precise slope calculation that had better ability to reveal group-wise differences. Second, Mehraei et al. related their slope measure to Wave I amplitude growth, rather than to an absolute amplitude measure. Therefore, amplitude growth may be a more sensitive measure of synaptopathy than absolute amplitude; however, given lower test-retest reliability in relative measures, amplitude growth may not be a clinically feasible measure (Guest et al., 2019).

Frequency-following response

The age-related reduction in phase locking to the steady-state vowel was consistent with previous studies (Anderson et al., 2012; Bidelman et al., 2014; Mamo et al., 2016; Presacco et al., 2016; Presacco et al., 2015; Roque et al., 2019a). We had hypothesized that we would see a greater reduction in phase locking in the ONH listeners for the longer vowel than for the shorter vowel, and we did not observe this difference between syllables. Instead, we found that phase locking in the ONH listeners declined over time (phase locking was greater in the earlier regions of the vowel compared to the later regions) for both vowels. In contrast, the strength of phase locking in the YNH listeners maintained throughout the duration of the vowel in both syllables. We used a consonant-vowel syllable in the current study in contrast to the vowel used in the Presacco (2015) study, which may be one reason for the lack of replication of the differential effect of vowel length. Another factor may be that the ONH listeners in the Presacco study had slightly worse hearing in the higher frequencies (6 kHz and 8 kHz) than the ONH listeners in the current study, and perhaps the increased high-frequency hearing loss in the Presacco study was an indication of poorer peripheral function, leading to a more pronounced in decrease in sustained neural firing than we found in the current study. Finally, the lack of replication may be due to a false discovery error. The Presacco study included 15 ONH participants and the reduction in phase locking was noted in approximately half of the participants; this finding may have occurred by chance.

Factors contributing to phase locking strength

Outer hair cell function (DPOAEs) was the only measure that significantly contributed to phase-locking strength in responses to the 260-ms /ba/ syllable in the linear regression model. DPOAEs only accounted for 14% of the variance in phase locking, however, so other variables that were not assessed in the current study may be important factors. For example, cortical auditory evoked potentials to the same stimuli could demonstrate top-down enhancement of phase locking strength that is more pronounced in younger than in older listeners. Or, the evaluation of age-related changes in single units in the brainstem or midbrain may reveal subcortical neural mechanisms that underlie decreased phase locking strength in older listeners. For example, Schatteman et al. (2008) found age-related changes in coding of sinusoidally amplitude modulated tones in dorsal cochlear nucleus neurons of rats. Similar effects were induced by blocking glycinergic inhibition. Therefore, age-related decreases in inhibitory neurotransmission may underlie decreased phase locking strength in older listeners. Furthermore, we acknowledge that we cannot completely rule out auditory nerve function in our findings, as the surface recordings that we chose may not be sensitive enough to reveal associations between measures. For example, amplitude growth may be a more effective correlate of synaptopathy. In an aging mouse model, cochlear synaptopathy was correlated with degraded neural processing at early levels of the auditory system

(Parthasarathy and Kujawa, 2018). A cross-species study would enable a better understanding of decreased phase locking in older human listeners by combining results from surface recordings in humans with single unit recordings in animals to elucidate mechanisms.

Sex differences

Although the older and young listeners did not significantly differ in sex distribution, the overall number of females across groups was higher (46) than the number of males (14). This unequal distribution limits our ability to draw inferences regarding sex effects. There were no sex differences observed across any of our ABR or FFR measures. However, the scatter plots in Figure 7 demonstrate that the relationship between phase-locking strength and DPOAEs is largely driven by data in the male listeners – higher DPOAE thresholds relate to lower PLF. We did not explicitly categorize hearing loss by phenotype, but it is possible that males demonstrated a hearing loss phenotype (audiogram configuration) that affects phase locking. For example, if more male audiograms were classified as a sensory phenotype that is predominantly high-frequency (Dubno et al., 2013), then perhaps damage to the base of the basilar membrane is a greater contributor to decreased phase locking.

Conclusion

Older listeners have delayed ABR latencies, reduced ABR amplitudes, and degraded FFR phase locking compared to younger listeners, and these age differences appear to be somewhat independent of differences in outer hair cell function. We found that DPOAEs contributed to phase-locking strength across listeners, although the predicted variance was rather small. Despite the uncertainty regarding the factors contributing to phase locking strength, it is important to note that the older listeners had pronounced reductions in phase locking overall compared to the young listeners. The older listeners all had normal to near normal hearing thresholds. Yet, the presence of reduced phase locking suggests that there is age-related signal degradation in the auditory pathway that may interfere with speech understanding, especially if the aging cortex only partially compensates for the degraded signal (Anderson et al., 2020).

ACKNOWLEDGEMENTS

The authors wish to thank Lindsey Roque, Abigail Poe, and Caitlin Le for their assistance with data collection and analysis.

Funding Information. This study was supported by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health (NIH) under award number R21DC015843 (Anderson). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Abbreviations:

ABR	Auditory brainstem response
FFR	Frequency-following response
PLF	Phase-locking factor

PTA	Pure-tone average
HF	high frequency
SNR	signal-to-noise ratio
DPOAEs	distortion-product otoacoustic emissions
DPAVG	distortion-product average
YNH	young normal-hearing
ONH	older normal-hearing
ICCs	Intra-class correlation coefficients

References

Abdala C, Dhar S 2012. Maturation and aging of the human cochlea: A view through the dpoae looking glass. Journal of the Association for Research in Otolaryngology 13, 403–421, 10.1007/s10162-012-0319-2. [PubMed: 22476702]

Anderson S, Parbery-Clark A, White-Schwoch T, Kraus N 2012. Aging affects neural precision of speech encoding. J. Neurosci. 32, 14156–14164, 10.1523/jneurosci.2176-12.2012. [PubMed: 23055485]

Anderson S, Roque L, Gaskins CR, Gordon-Salant S, Goupell MJ 2020. Age-related compensation mechanism revealed in the cortical representation of degraded speech. J. Assoc. Res. Otolaryngol, 10.1007/s10162-020-00753-4.

Benjamini Y, Hochberg Y 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society. Series B (Methodological), 289–300, https://www.jstor.org/stable/2346101.

Bidelman GM, Villafuerte JW, Moreno S, Alain C 2014. Age-related changes in the subcortical-cortical encoding and categorical perception of speech. Neurobiol. Aging, 10.1016/j.neurobiolaging.2014.05.006.

Bieber RE, Fernandez K, Zalewski C, Cheng H, Brewer CC 2020. Stability of early auditory evoked potential components over extended test-retest intervals in young adults. Ear Hear, 10.1097/aud.0000000000000872.

Billings CJ, Penman TM, McMillan GP, Ellis EM 2015. Electrophysiology and perception of speech in noise in older listeners: Effects of hearing impairment and age. Ear Hear. 36, 710–22, 10.1097/aud.0000000000000191. [PubMed: 26502191]

Boersma P, Weenink D 2009. Praat: Doing phonetics by computer (Version 5.1. 05)[Computer program]. Retrieved May 1, 2009.

Boettcher FA, Mills JH, Norton BL 1993. Age-related changes in auditory evoked potentials of gerbils. I. Response amplitudes. Hear. Res 71, 137–145, 10.1016/0378-5955(93)90029-z. [PubMed: 8113132]

Boothroyd A, Medwetsky L 1992. Spectral distribution of /s/ and the frequency response of hearing aids. Ear Hear. 13, 150–7, 10.1097/00003446-199206000-00003. [PubMed: 1397754]

Boothroyd A, Erickson FN, Medwetsky L 1994. The hearing aid input: A phonemic approach to assessing the spectral distribution of speech. Ear Hear. 15, 432–42, 10.1097/00003446-199412000-00004. [PubMed: 7895939]

Bramhall N, Ong B, Ko J, Parker M 2015. Speech perception ability in noise is correlated with auditory brainstem response wave i amplitude. J. Am. Acad. Audiol 26, 509–17, 10.3766/jaaa.14100. [PubMed: 26055840]

Bramhall N, Beach EF, Epp B, Le Prell CG, Lopez-Poveda EA, Plack CJ, Schaette R, Verhulst S, Canlon B 2019. The search for noise-induced cochlear synaptopathy in humans: Mission impossible? Hear. Res 377, 88–103, 10.1016/j.heares.2019.02.016. [PubMed: 30921644]

Bramhall NF, Konrad-Martin D, McMillan GP, Griest SE 2017. Auditory brainstem response altered in humans with noise exposure despite normal outer hair cell function. Ear Hear. 38, e1–e12, 10.1097/aud.0000000000000370. [PubMed: 27992391]

Burkard RF, Sims D 2001. The human auditory brainstem tesponse to high click rates: Aging effects. Am. J. Audiol 10, 53–61, 10.1044/1059-0889(2001/008). [PubMed: 11808720]

Cai R, Montgomery SC, Graves KA, Caspary DM, Cox BC 2018. The FBN rat model of aging: investigation of ABR waveforms and ribbon synapse changes. Neurobiol. Aging 62, 53–63, 10.1016/j.neurobiolaging.2017.09.034. [PubMed: 29107847]

Carhart R, Jerger J 1959. Preferred method for clinical determination of pure-tone thresholds. Journal of Speech and Hearing Disorders 24, 330–345,

CHABA. 1988. Speech understanding and aging. J. Acoust. Soc. Am. 83, 859–895, 10.1121/1.395965. [PubMed: 3281988]

Chambers AR, Resnik J, Yuan Y, Whitton JP, Edge AS, Liberman MC, Polley DB 2016. Central gain restores auditory processing following near-complete cochlear denervation. Neuron 89, 867–79, 10.1016/j.neuron.2015.12.041. [PubMed: 26833137]

Dau T 2003. The importance of cochlear processing for the formation of auditory brainstem and frequency following responses. J. Acoust. Soc. Am. 113, 936–50, 10.1121/1.1534833. [PubMed: 12597187]

Delorme A, Makeig S 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods 134, 9–21, 10.1016/j.jneumeth.2003.10.009. [PubMed: 15102499]

Dubno JR, Eckert MA, Lee FS, Matthews LJ, Schmiedt RA 2013. Classifying human audiometric phenotypes of age-related hearing loss from animal models. J. Assoc. Res. Otolaryngol. 14, 687–701, 10.1007/s10162-013-0396-x. [PubMed: 23740184]

Eddins AC, Eddins DA 2018. Cortical correlates of binaural temporal processing deficits in older adults. Ear Hear. 39, 594–604, 10.1097/aud.0000000000000518. [PubMed: 29135686]

Fabijańska A, Smurzyński J, Hatzopoulos S, Kochanek K, Bartnik G, Raj-Koziak D, Mazzoli M, Skarżyński PH, Jędrzejczak WW, Szkiełkowska A, Skarżyński H 2012. The relationship between distortion product otoacoustic emissions and extended high-frequency audiometry in tinnitus patients. Part 1: normally hearing patients with unilateral tinnitus. Med. Sci. Monit 18, CR765–CR770, 10.12659/msm.883606. [PubMed: 23197241]

Frisina RD, Singh A, Bak M, Bozorg S, Seth R, Zhu X 2011. F1 (CBA × C57) mice show superior hearing in old age relative to their parental strains: hybrid vigor or a new animal model for “golden ears”? Neurobiol. Aging 32, 1716–1724, 10.1016/j.neurobiolaging.2009.09.009. [PubMed: 19879021]

Gaskins C, Jaekel BN, Gordon-Salant S, Goupell MJ, Anderson S 2019. Effects of aging on perceptual and electrophysiological responses to acoustic pulse trains as a function of rate. J. Speech Lang. Hear. Res 62, 1087–1098, 10.1044/2018_jslhr-h-ascc7-18-0133. [PubMed: 31026191]

Goossens T, Vercammen C, Wouters J, van Wieringen A 2016. Aging affects neural synchronization to speech-related acoustic modulations. Front. Aging Neurosci. 8, 133, 10.3389/fnagi.2016.00133. [PubMed: 27378906]

Grose JH, Buss E, Elmore H 2019. Age-related changes in the auditory brainstem response and suprathreshold processing of temporal and spectral modulation. Trends Hear. 23, 2331216519839615, 10.1177/2331216519839615. [PubMed: 30977442]

Guest H, Munro KJ, Prendergast G, Plack CJ 2019. Reliability and interrelations of seven proxy measures of cochlear synaptopathy. Hear. Res. 375, 34–43, 10.1016/j.heares.2019.01.018. [PubMed: 30765219]

Hao W, Wang Q, Li L, Qiao Y, Gao Z, Ni D, Shang Y 2018. Effects of phase-locking deficits on speech recognition in older adults with presbycusis. Front. Aging Neurosci. 10, 397, 10.3389/fnagi.2018.00397. [PubMed: 30574084]

Harris KC, Dubno JR 2017. Age-related deficits in auditory temporal processing: Unique contributions of neural dyssynchrony and slowed neuronal processing. Neurobiol. Aging 53, 150–158, 10.1016/j.neurobiolaging.2017.01.008. [PubMed: 28185661]

JASP. 2018. JASP Team, 0.9 ed.

Jenkins KA, Fodor C, Presacco A, Anderson S 2018. Effects of amplification on neural phase locking, amplitude, and latency to a speech syllable. Ear Hear. 39, 810–824, 10.1097/aud.0000000000000538. [PubMed: 29287038]

Jerger J, Hall J 1980. Effects of age and sex on auditory brainstem response. Arch. Otolaryngol. 106, 387–391, 10.1001/archotol.106.7.387. [PubMed: 7387524]

Jewett DL, Williston JS 1971. Auditory-evoked far fields averaged from the scalp of humans. Brain 94, 681–96, 10.1093/brain/94.4.681. [PubMed: 5132966]

Jilek M, Šuta D, Syka J 2014. Reference hearing thresholds in an extended frequency range as a function of age. J. Acoust. Soc. Am. 136, 1821–1830, 10.1121/1.4894719. [PubMed: 25324083]

Joris PX, Smith PH 2008. The volley theory and the spherical cell puzzle. Neuroscience 154, 65–76, 10.1016/j.neuroscience.2008.03.002. [PubMed: 18424004]

Konrad-Martin D, Dille MF, McMillan G, Griest S, McDermott D, Fausti SA, Austin DF 2012. Age-related changes in the auditory brainstem response. J. Am. Acad. Audiol. 23, 18–35, 10.3766/jaaa.23.1.3. [PubMed: 22284838]

Krizman J, Skoe E, Kraus N 2012. Sex differences in auditory subcortical function. Clinical Neurophysiology 123, 590–597, 10.1016/j.clinph.2011.07.037. [PubMed: 21855407]

Kujawa SG, Liberman MC 2009. Adding insult to injury: Cochlear nerve degeneration after “temporary” noise-induced hearing loss. J. Neurosci. 29, 14077–14085, 10.1523/jneurosci.2845-09.2009. [PubMed: 19906956]

Lin HW, Furman AC, Kujawa SG, Liberman MC 2011. Primary neural degeneration in the Guinea pig cochlea after reversible noise-induced threshold shift. J. Assoc. Res. Otolaryngol. 12, 605–16, 10.1007/s10162-011-0277-0. [PubMed: 21688060]

Makary CA, Shin J, Kujawa SG, Liberman MC, Merchant SN 2011. Age-related primary cochlear neuronal degeneration in human temporal bones. J. Assoc. Res. Otolaryngol. 12, 711–7, 10.1007/s10162-011-0283-2. [PubMed: 21748533]

Mamo SK, Grose JH, Buss E 2016. Speech-evoked ABR: Effects of age and simulated neural temporal jitter. Hear. Res. 333, 201–9, 10.1016/j.heares.2015.09.005. [PubMed: 26368029]

McClaskey CM, Dias JW, Harris KC 2019. Sustained envelope periodicity representations are associated with speech-in-noise performance in difficult listening conditions for younger and older adults. J. Neurophysiol, 10.1152/jn.00845.2018.

Mehraei G, Hickox AE, Bharadwaj HM, Goldberg H, Verhulst S, Liberman MC, Shinn-Cunningham BG 2016. Auditory brainstem response latency in noise as a marker of cochlear synaptopathy. J. Neurosci. 36, 3755–64, 10.1523/jneurosci.4460-15.2016. [PubMed: 27030760]

Mitchell C, Phillips DS, Trune DR 1989. Variables affecting the auditory brainstem response: Audiogram, age, gender and head size. Hear. Res 40, 75–85, 10.1016/0378-5955(89)90101-9. [PubMed: 2768085]

Motlagh Zadeh L, Silbert NH, Sternasty K, Swanepoel W, Hunter LL, Moore DR 2019. Extended high-frequency hearing enhances speech perception in noise. Proc. Natl. Acad. Sci. U S A, 10.1073/pnas.1903315116.

Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, Cummings JL, Chertkow H 2005. The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. J. Am. Geriatr. Soc 53, 695–699, 10.1111/j.1532-5415.2005.53221.x. [PubMed: 15817019]

Overton JA, Recanzone GH 2016. Effects of aging on the response of single neurons to amplitude-modulated noise in primary auditory cortex of rhesus macaque. J. Neurophysiol. 115, 2911–23, 10.1152/jn.01098.2015. [PubMed: 26936987]

Parthasarathy A, Kujawa SG 2018. Synaptopathy in the aging cochlea: Characterizing early-neural deficits in auditory temporal envelope processing. J. Neurosci. 38, 7108–7119, 10.1523/jneurosci.3240-17.2018. [PubMed: 29976623]

Parthasarathy A, Datta J, Torres JA, Hopkins C, Bartlett EL 2014. Age-related changes in the relationship between auditory brainstem responses and envelope-following responses. J. Assoc. Res. Otolaryngol. 15, 649–61, 10.1007/s10162-014-0460-1. [PubMed: 24845405]

Prabhu P, Banerjee N, Anil A, Abdulla A 2016. Role of sex hormones produced during menstrual cycle on brainstem encoding of speech stimulus. European Archives of Oto-Rhino-Laryngology 273, 3647–3650, 10.1007/s00405-016-4009-2. [PubMed: 27015668]

Presacco A, Simon JZ, Anderson S 2016. Evidence of degraded representation of speech in noise, in the aging midbrain and cortex. J. Neurophysiol. 116, 2346–2355, 10.1152/jn.00372.2016. [PubMed: 27535374]

Presacco A, Jenkins K, Lieberman R, Anderson S 2015. Effects of aging on the encoding of dynamic and static components of speech. Ear Hear. 36, e352–63, 10.1097/aud.0000000000000193. [PubMed: 26177213]

Roque L, Karawani H, Gordon-Salant S, Anderson S 2019a. Effects of age, cognition, and neural encoding on the perception of temporal speech cues. Front. Neurosci 13, 749, 10.3389/fnins.2019.00749. [PubMed: 31379494]

Roque L, Gaskins C, Gordon-Salant S, Goupell MJ, Anderson S 2019b. Age effects on neural representation and perception of silence duration cues in speech. J. Speech Lang. Hear. Res 62, 1099–1116, 10.1044/2018_jslhr-h-ascc7-18-0076. [PubMed: 31026197]

Schatteman TA, Hughes LF, Caspary DM 2008. Aged-related loss of temporal processing: Altered responses to amplitude modulated tones in rat dorsal cochlear nucleus. Neuroscience 154, 329–337, 10.1016/j.neuroscience.2008.02.025. [PubMed: 18384967]

Schmiedt RA, Mills JH, Boettcher FA 1996. Age-related loss of activity of auditory-nerve fibers. J. Neurophysiol 76, 2799–2803, 10.1152/jn.1996.76.4.2799. [PubMed: 8899648]

Sergeyenko Y, Lall K, Liberman MC, Kujawa SG 2013. Age-related cochlear synaptopathy: An early-onset contributor to auditory functional decline. J. Neurosci. 33, 13686–13694, 10.1523/jneurosci.1783-13.2013. [PubMed: 23966690]

Skoe E, Krizman J, Anderson S, Kraus N 2015. Stability and plasticity of auditory brainstem function across the lifespan. Cereb. Cortex 25, 1415–26, 10.1093/cercor/bht311. [PubMed: 24366906]

Smith SB, Krizman J, Liu C, White-Schwoch T, Nicol T, Kraus N 2019. Investigating peripheral sources of speech-in-noise variability in listeners with normal audiograms. Hear. Res. 371, 66–74, https://10.1016/j.heares.2018.11.008. [PubMed: 30504092]

Stelmachowicz PG, Beauchaine KA, Kalberer A, Jesteadt W 1989. Normative thresholds in the 8- to 20- kHz range as a function of age. J. Acoust. Soc. Am. 86, 1384–1391, 10.1121/1.398698. [PubMed: 2808912]

Stevens KN 1998. Acoustic phonetics MIT Press, Cambridge, Mass.

Tallon-Baudry C, Bertrand O, Delpuech C, Pernier J 1996. Stimulus specificity of phase-locked and non-phase-locked 40 hz visual responses in human. J. Neurosci. 16, 4240–4249, 10.1523/JNEUROSCI.16-13-04240.1996. [PubMed: 8753885]

Torre P 3rd, Fowler CG 2000. Age-related changes in auditory function of rhesus monkeys (Macaca mulatta). Hear. Res. 142, 131–40, 10.1016/s0378-5955(00)00025-3. [PubMed: 10748335]

Uchida Y, Ando F, Shimokata H, Sugiura S, Ueda H, Nakashima T 2008. The effects of aging on distortion-product otoacoustic emissions in adults with normal hearing. Ear Hear. 29, 176–84, 10.1097/aud.0b013e3181634eb8. [PubMed: 18595184]

Vercammen C, Goossens T, Undurraga J, Wouters J, van Wieringen A 2018. Electrophysiological and behavioral evidence of reduced binaural temporal processing in the aging and hearing impaired human auditory system. Trends Hear. 22, 2331216518785733, 10.1177/2331216518785733. [PubMed: 30022734]

Viana LM, O'Malley JT, Burgess BJ, Jones DD, Oliveira CA, Santos F, Merchant SN, Liberman LD, Liberman MC 2015. Cochlear neuropathy in human presbycusis: Confocal analysis of hidden hearing loss in post-mortem tissue. Hear. Res. 327, 78–88, 10.1016/j.heares.2015.04.014. [PubMed: 26002688]

Walton JP, Frisina RD, O'Neill WE 1998. Age-related alteration in processing of temporal sound features in the auditory midbrain of the CBA mouse. J. Neurosci. 18, 2764–2776, 10.1523/JNEUROSCI.18-07-02764.1998. [PubMed: 9502833]

Wang H, Brozoski TJ, Caspary DM 2011. Inhibitory neurotransmission in animal models of tinnitus: maladaptive plasticity. Hear. Res. 279, 111–7, 10.1016/j.heares.2011.04.004. [PubMed: 21527325]

Willott JF 1991. Central physiological correlates of ageing and presbycusis in mice. Acta Oto-laryngologica 111, 153–156, 10.3109/00016489109127271. [PubMed: 2014752]

Wu PZ, Liberman LD, Bennett K, de Gruttola V, O'Malley JT, Liberman MC 2019. Primary neural degeneration in the human cochlea: Evidence for hidden hearing loss in the aging ear. Neuroscience 407, 8–20, 10.1016/j.neuroscience.2018.07.053. [PubMed: 30099118]

Yeend I, Beach EF, Sharma M 2019. Working memory and extended high-frequency hearing in adults: Diagnostic predictors of speech-in-noise perception. Ear Hear. 40, 458–467, 10.1097/aud.0000000000000640. [PubMed: 30052557]

Zhu J, Garcia E 1999. The Wechsler Abbreviated Scale of Intelligence (WASI) Psychological Corporation, New York.

Highlights

- Normal-hearing older individuals have delayed auditory brainstem responses
- Phase locking is reduced in older listeners compared to younger listeners
- Auditory brainstem response variables contribute to variance in phase locking

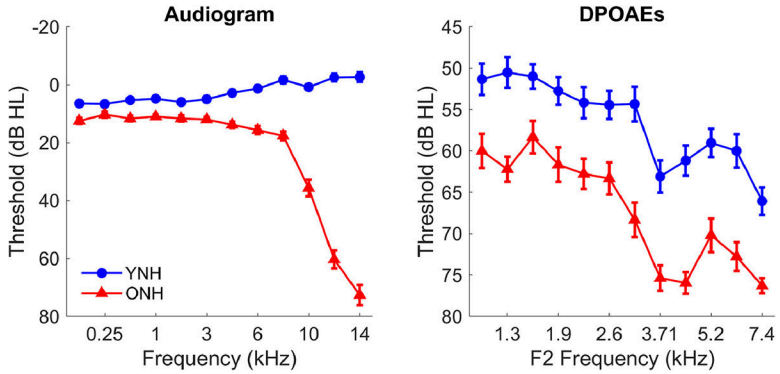

Fig. 1.

Audiometric and distortion product otoacoustic emissions (DPOAEs) thresholds are elevated in older normal-hearing listeners (ONH, red triangles) compared to younger normal-hearing listeners (YNH, blue circles) across the frequency range, but the group differences widen above 3 kHz (audiogram) and above 2. 6 kHz (DPOAEs). Error bars: ± 1 Standard Error.

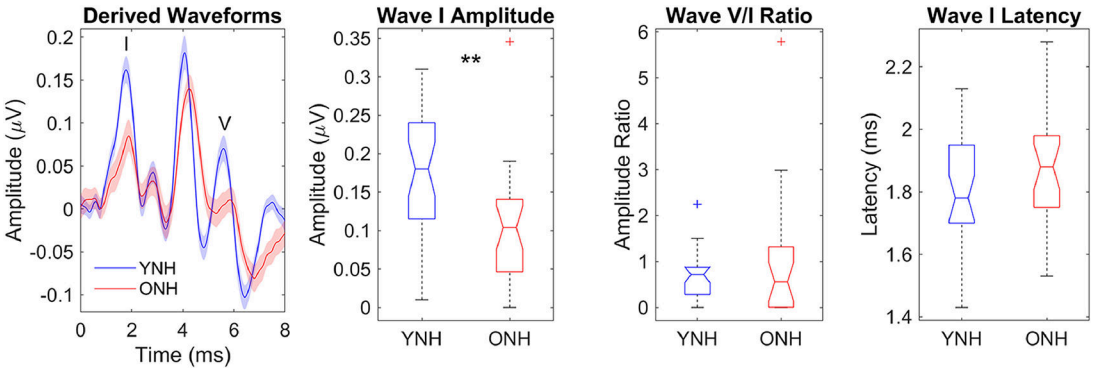

Fig. 2.

Auditory nerve function. The average auditory brainstem response (ABR) waveforms in the left-most plot (obtained with derived horizontal montage) show that overall amplitude is lower in ONH (red) compared to YNH (blue) listeners. Shaded regions: ± 1 Standard Error. The notched box plots compare Wave I amplitude, Wave V/I ratio, and Wave I latency between ONH and YNH participants. Wave I amplitude is significantly higher in the ONH compared to the YNH participants. **$p < 0.01$.

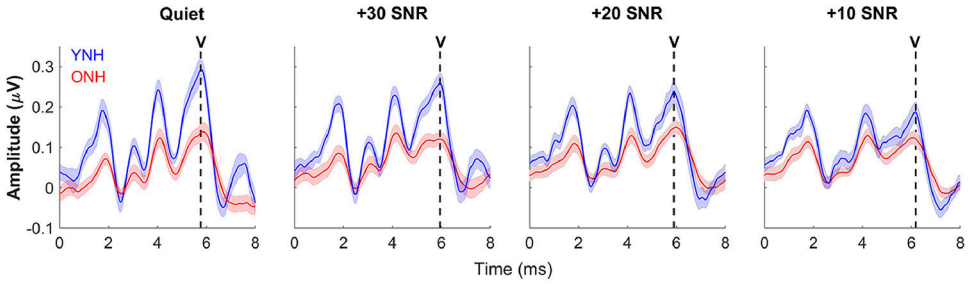

Fig. 3.

Aging effects on Wave V. The average ABR waveforms (vertical montage) obtained in quiet and in white noise at +30, +20, and +10 dB SNR show that in ONH listeners, overall amplitudes are lower and Wave V latencies are delayed across conditions compared to the YNH listeners. Shaded regions: ± 1 Standard Error. The dashed line in each plot was placed at the mean latency in the YNH listeners.

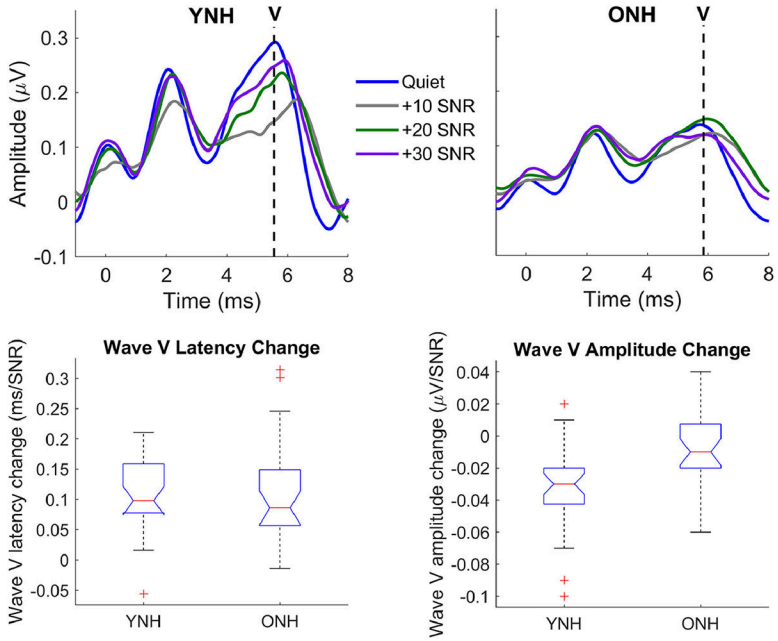

Fig. 4.

Noise effects on Wave V. Top panel: Average ABR waveforms across quiet and decreasing SNR conditions are overlaid separately in ONH and OHI groups. Changes in latency and amplitude are apparent in the YNH listeners but not in the ONH listeners. Bottom panel: Notched box plots are displayed for the slope of change in Wave V with decreasing SNRs for latency and amplitude in YNH and ONH listeners. The ONH listeners have shallower slopes than the YNH listeners for the amplitude decrease, but the slopes are not statistically different between the groups for the latency increase.

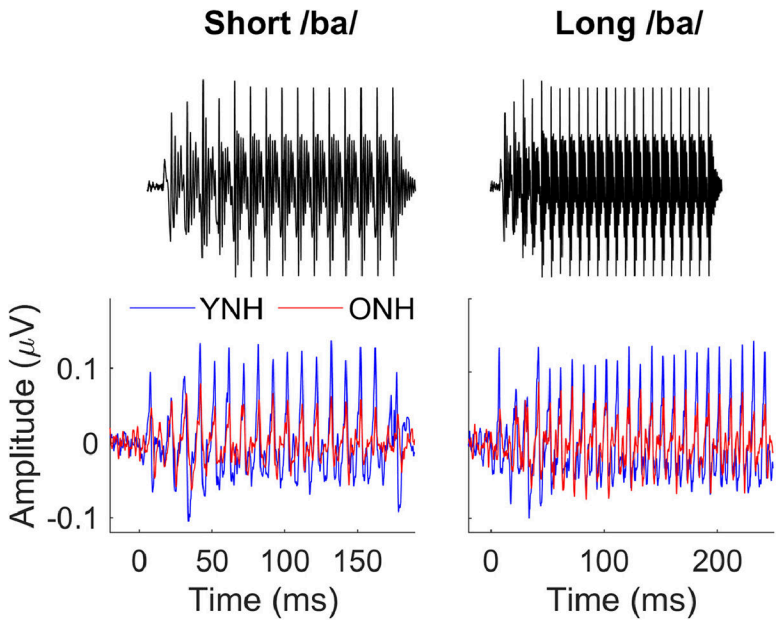

Fig. 5.

Top panel: Stimulus waveforms are displayed for the shorter 170-ms /ba/ and the longer 260-ms /ba/. Bottom panel: Average response waveforms corresponding to the shorter and longer /ba/ stimuli are displayed for the YNH (blue) and ONH (red) listeners. Note that the periodicity of the stimuli is mirrored in the responses. An age-related reduction in response amplitude is apparent in the response waveforms.

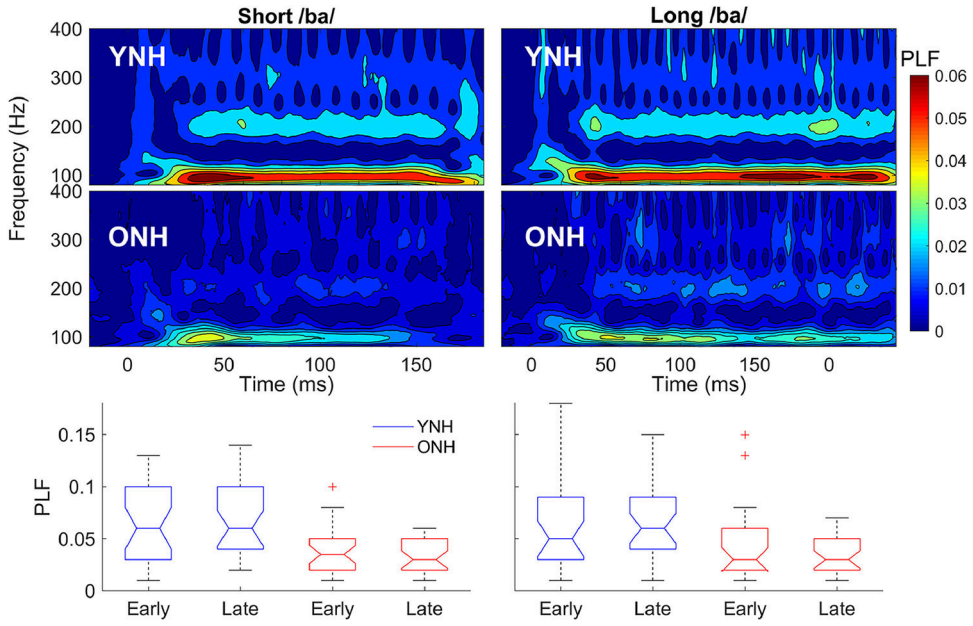

Fig. 6.

Top panel: Average phase-locking factor (PLF) to the temporal envelope of the shorter 170-ms /ba/ and the longer 260-ms /ba/ represented in the time-frequency domain, with hotter colors representing higher phase locking in YNH and ONH listeners. Age-related PLF reductions are observed for both syllabi. Bottom panel: Notched box plots are displayed for the PLF corresponding to the early and late regions of the steady-state vowels of the /ba/ stimuli in YNH (blue) and OHI (red) listeners.

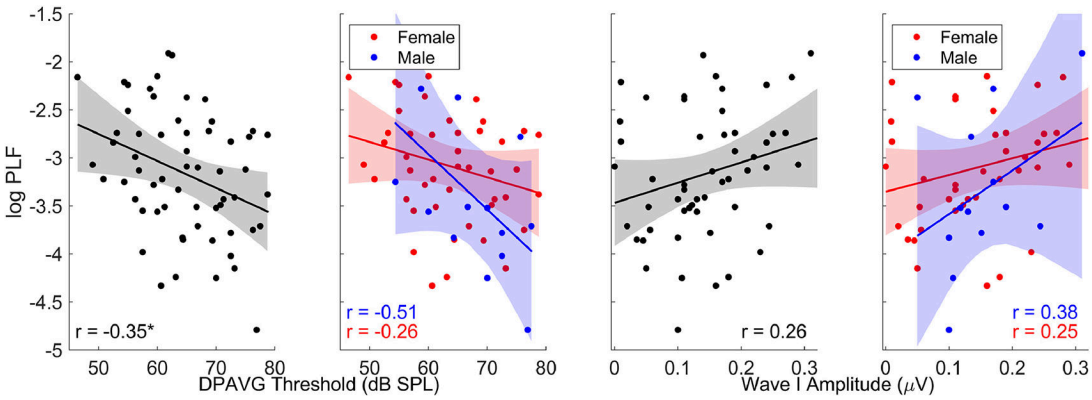

Fig. 7.

Scatter plots demonstrating relationships among phase-locking factor (PLF) and distortion-product otoacoustic emission average (DPAVG) and Wave I amplitude across groups and within male (blue) and female (red) groups. DPAVG was positively correlated with PLF. *p < 0.05. Shaded region: Confidence interval (α=0.05).

Table 1.

Standardized (β) coefficient in a model automatically generated by evaluating the significance of each variable's contribution to the 260-ms /ba/ phase-locking factor (PLF). The distortion product otoacoustic emissions average (DPAVG) significantly contributed to variance in PLF. Wave I amplitude, Sex, and DPAVG × Wave I amplitude were excluded from the model.

"Summary of "Stepwise" Regression Analysis for Variables Contributing to the 260-ms /ba/ Phase-Locking Factor (PLF)."			
Variable	R^2 change	β	p value
Model 1	0.14		0.007
DPAVG		−0.37	0.007
Excluded Variables		**β**	**p value**
Wave I		0.25	0.073
Sex		−0.03	0.821
Wave I × DPAVG		0.26	0.051