Neurobiology of Aging 35 (2014) 2526–2540

Contents lists available at ScienceDirect

Neurobiology of Aging

journal homepage: www.elsevier.com/locate/neuaging

Age-related changes in the subcortical–cortical encoding and categorical perception of speech

Gavin M. Bidelman [a,b,*], Joshua W. Villafuerte [c,d], Sylvain Moreno [c,d], Claude Alain [c,d,e]

[a] Institute for Intelligent Systems, University of Memphis, Memphis, TN, USA
[b] School of Communication Sciences & Disorders, University of Memphis, Memphis, TN, USA
[c] Rotman Research Institute, Baycrest Centre for Geriatric Care, Toronto, Ontario, Canada
[d] Department of Psychology, University of Toronto, Toronto, Ontario, Canada
[e] Institute of Medical Sciences, University of Toronto, Ontario, Canada

ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 7 April 2014
Accepted 2 May 2014
Available online 10 May 2014

Keywords:
Cognitive aging
Auditory event-related potentials (ERPs)
Categorical speech perception
Brainstem frequency-following response (FFR)
Mutual information (MI)
Speech perception
Brain signal variability

ABSTRACT

Aging is associated with declines in auditory processing including speech comprehension abilities. Here, we evaluated both brainstem and cortical speech-evoked brain responses to elucidate how aging impacts the neural transcription and transfer of speech information between functional levels of the auditory nervous system. Behaviorally, older adults showed slower, more variable speech classification performance than younger listeners, which coincided with reduced brainstem amplitude and increased, but delayed, cortical speech-evoked responses. Mild age-related hearing loss showed differential correspondence with neurophysiological responses showing negative (brainstem) and positive (cortical) correlations with brain activity. Spontaneous brain activity, that is, "neural noise," did not differ between older and younger adults. Yet, mutual information and correlations computed between brainstem and cortex revealed higher redundancy (i.e., lower interdependence) in speech information transferred along the auditory pathway implying less neural flexibility in older adults. Results are consistent with the notion that weakened speech encoding in brainstem is overcompensated by increased cortical dysinhibition in the aging brain. Findings suggest aging negatively impacts speech listening abilities by distorting the hierarchy of speech representations, reducing neural flexibility through increased neural redundancy, and ultimately impairing the acoustic-phonetic mapping necessary for robust speech understanding.

1. Introduction

Normal aging is associated with declines in auditory processing including listening skills necessary for robust speech understanding (Gordon-Salant and Fitzgibbons, 1993; Konkle et al., 1977; Strouse et al., 1998). Poorer comprehension in elderly individuals could arise from multiple sources including concomitant changes in higher-level cognitive processes (e.g., memory, attention allocation, and distractibility) and lower level sensory-perceptual mechanisms (Schneider et al., 2002). Both peripheral hearing loss and/or reduced cognitive flexibility may contribute to the speech processing deficits that emerge late into life (Humes, 1996; Humes et al., 2012). However, emerging evidence indicates that even in the absence of hearing and cognitive impairment, speech listening remains a formidable challenge for elderly individuals (Gordon-Salant and Fitzgibbons, 1993; Hutka et al., 2013; Konkle et al., 1977; Schneider et al., 2002; Strouse et al., 1998; van Rooij and Plomp, 1992). These findings challenge conventional and longstanding views that older adults' speech intelligibility issues arise solely from audibility (i.e., hearing sensitivity) or cognitive capacity (Humes, 1996; Plomp, 1986). Instead, they suggest that perceptual deficits arise because of impoverished sensory encoding and transmission of speech information within the central nervous system (Peelle et al., 2011; Schneider et al., 2002; Wong et al., 2010). The importance of central factors in speech recognition is evident in the shortcomings of current assistive hearing technologies (e.g., hearing aids), which fail to fully restore speech understanding, particularly in noise, despite supplying adequate audibility (Chmiel and Jerger, 1996; Ricketts and Hornsby, 2005). Understanding how speech signals are translated from external acoustic energy to internalized sound "objects", and how aging affects this process, is essential for the design of more effective therapeutic interventions to improve or maintain speech listening abilities late into life.

* Corresponding author at: School of Communication Sciences & Disorders, University of Memphis, 807 Jefferson Ave., Memphis, TN 38105, USA. Tel.: +1 901 678 5826; fax: +1 901 525 1282.
E-mail address: g.bidelman@memphis.edu (G.M. Bidelman).

0197-4580/$ – see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.neurobiolaging.2014.05.006

Effective speech understanding requires that the auditory system faithfully transcribe acoustic information and maintain these neural representations through various signal transformations from periphery to percept. Classic models of speech perception often include "distortion" factors to account for the effects of aging (Plomp, 1986). Such distortions may result from the known declines in neural inhibition (Caspary et al., 2008; Parthasarathy and Bartlett, 2011) and increased deafferentation (Kujawa and Liberman, 2006; Makary et al., 2011) that occur along the aging mammalian auditory nervous system. In humans, neuroimaging studies reveal altered auditory cortical representations of speech in older listeners with and without hearing loss (Alain and Snyder, 2008; Snyder and Alain, 2005; Tremblay et al., 2002, 2003). Although there is evidence for age-related changes in brainstem activity for speech sounds (Anderson et al., 2012; Parbery-Clark et al., 2012), the relation between these and age-related effects on cortical representations of speech has yet to be established. Under investigation here are potential differential effects of age on the hierarchy of speech representations and signal transformations along the auditory pathway. Under normal circumstances, neural representations along the ascending auditory pathway are made less redundant (i.e., more abstract) at successive stages so as to allow for easier readout in higher-level structures (Chechik et al., 2006). We hypothesized that older adults' difficulties in speech understanding might be attributable not only to local distortions in sensory transcription at subcortical and cortical stages of processing but more critically, a redundancy in information transferred between these two levels of the auditory brain, that is, a higher similarity between successive neural representations.

Classical models of cognitive aging often include descriptions of the so-called neural-noise hypothesis (Mireles and Charness, 2002; Salthouse and Lichty, 1985; Welford, 1981). This premise suggests that perceptual-cognitive decline in aging is accompanied by a decrease in signal-to-noise ratio (i.e., increased neural noise) in the central nervous system which may in turn underlie the speech deficits associated with age (Alain and Woods, 1999; Salthouse and Lichty, 1985; Welford, 1981). In apparent support of this proposition, recent studies have reported an age-dependent change in electroencephalography (EEG) activity (i.e., "neural noise") in the aged brain (Anderson et al., 2012; Skoe et al., 2013a, 2013b). These findings have been interpreted as reflecting an increase in spontaneous brain activity in older adults, leading to a poorer, more variable translation of sensory information across the brain (e.g., Skoe et al., 2013b). Unfortunately, in quantifying EEG noise, these studies have examined neuroelectric amplitudes in the interstimulus interval (ISI) between time-locked stimulus presentations (Anderson et al., 2012; Skoe et al., 2013a, 2013b). Between stimulus activity may not reflect spontaneous brain activity per se, but rather induced oscillatory activity produced by the repeated and ongoing stimulus train (Trainor et al., 2009). Induced brain activity is generated in speech recognition paradigms (Shahin et al., 2009) and varies with age (Shahin et al., 2010). Hence, we reexamined the topic of neural noise in the aging brain and its role in older adults' speech processing.

In the present study, we evaluated brainstem and cortical event-related potentials (ERPs) recorded in the same younger and older adults during a categorical speech perception (CP) task (Bidelman et al., 2013). Under normal circumstances, auditory processing results from a complex interplay between "bottom-up" and "top-down" influences; speech processing is subject to both proximal signal analysis (within brainstem and cortex) as well as distal modulatory feedback between these levels of processing (Tzounopoulos and Kraus, 2009; Yan et al., 2005). Our systems-level approach allows us to investigate the differential effects of age on the hierarchy of these neural speech representations along the auditory pathway in the same listeners, as well as the degree of information conveyed between successive stages of processing. Additionally, joint neuroelectric responses enable us to assess how changes in lower- and higher-level brain function individually or synergistically contribute to perceptual speech listening abilities. To our knowledge, this is the first study to examine correspondence between brainstem, cortical, and behavioral speech processing in the aged brain. We also explored the neural noise hypothesis of aging (Salthouse and Lichty, 1985). Recent measures of age-dependent changes in spontaneous EEG have been confounded in their interpretations as they are unable to disentangle potential changes in intrinsic noise from induced (i.e., non-evoked) brain responses (Anderson et al., 2012; Skoe et al., 2013a, 2013b).

Our findings reveal that normal aging produces dissociable effects in neural processing: weakened brainstem encoding concurrent with over-exaggerated neural responses from auditory cortex. Additionally, we find that aging does not increase spontaneous neural noise, per se (cf. Anderson et al., 2012; Skoe et al., 2013b). Rather, we report a higher redundancy between levels of neural representation in the aged brain as revealed by increased correlation and mutual information between brainstem and cortical speech processing. Collectively, our findings provide a multi-tiered neurobiological account for the declines in speech comprehension that emerge later in life.

2. Methods

2.1. Participants

Thirteen young (age [mean ± standard deviation]: 25.5 ± 2.9 years; 10 female] and 13 older (69.30 ± 7.8 years; 7 female) adults were recruited from the University of Toronto and Greater Toronto Area to participate in the experiment (hereafter referred to as YA and OA, respectively). With the exception of age, the 2 groups were otherwise closely matched in demographics. All participants were strongly right-handed (Oldfield, 1971), reported no history of neurologic or psychiatric illnesses, and were matched in total years of formal education (YA: 17.5 ± 2.5 years, OA: 15.15 ± 3.5 years; $t_{24} = -1.970$, $p = 0.06$). Formal musical training and tone language experience can alter brainstem and cortical ERPs across the life span (Bidelman et al., 2011; Krishnan et al., 2010; Parbery-Clark et al., 2012; Strait et al., 2013). Thus, participants were required to be monolingual speakers of English (i.e., they were fluent in only a single language) with no formal training in music, defined as having ≤3 years of music lessons on any combination of instruments (YA: 0.31 ± 0.48 years, OA: 0.31 ± 0.63 years; $t_{24} = 0$, $p = 1$).

Hearing sensitivity was assessed using air-conduction audiometry following our previous reports (Alain et al., 2012; Bidelman and Krishnan, 2010; Hutka et al., 2013); bone-conducted thresholds were not obtained. Clinically normal hearing thresholds were defined as having a pure-tone average (average thresholds at 0.5, 1, 2 kHz) better than 25 dB HL (Brandy, 2002). For younger adults, no hearing loss was expected so an audiometric screening was performed at 15 dB HL across octave frequencies between 250 and 8000 Hz, bilaterally. Positive response to tone presentations confirmed younger adults' hearing was at or better than 15 dB HL across the board. All younger participants also reported no history of hearing-related issues. Older adults completed a more extensive audiometric evaluation to more fully characterize their hearing and identify suspected age-related hearing loss: complete air conduction thresholds were measured at octave frequencies between 250 and 8000 Hz. Despite their age, older adults on average, had clinically normal ($PTA_{LE} = 23.5 \pm 8.9$ dB HL; $PTA_{RE} = 22.7 \pm 6.4$ dB HL) and symmetric ($t_{24} = 0.253$, $p = 0.80$) hearing thresholds (Fig. 1). Two older participants showed slightly elevated PTAs (between 30

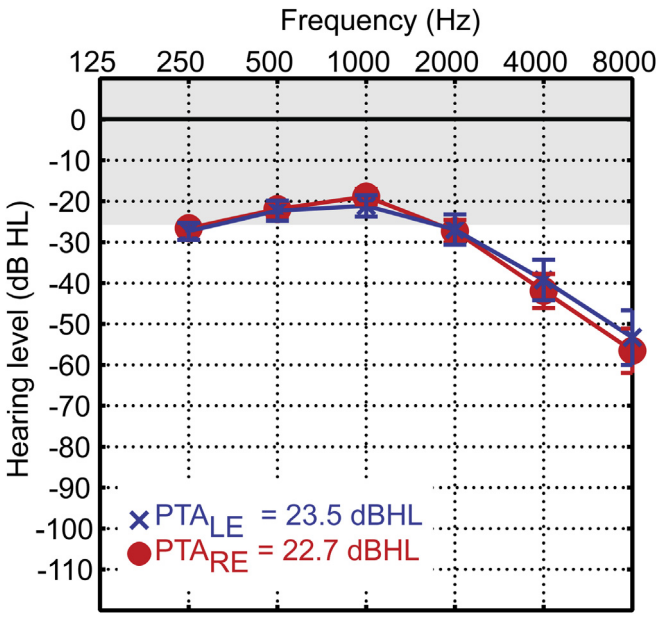

Fig. 1. Audiograms for older adults. Air conduction audiometric hearing thresholds revealed pure tone averages (mean of 500, 1000, and 2000 kHz) of 23.5 dB HL and 22.7 dB HL for the left and right ears, respectively. Based on a screening, all younger adults in the study had hearing at or better than 15 dB HL (not shown). Although slightly elevated relative to younger listeners, older adults' PTA hearing sensitivity was within clinically normal limits (≤25 dB HL, shaded region) across the frequency bandwidth of interest for our CP stimuli (i.e., <1000 Hz; see Fig. 2). Stimulus presentation level was determined in sensational level (dB SL) to equate hearing sensitivity between younger and older adults. Abbreviation: CP, categorical speech perception; PTA, pure-tone average.

and 40 dB HL). Above the stimulus frequency range of interest (i.e., >1000 Hz; see stimulus F1 frequencies, Fig. 2), older adults generally had some amount of high-frequency presbycusis, but this was limited to a mild-to-moderate loss. To rule out deficits in cognitive function, older adults were also screened for dementia and cognitive impairment using the Montreal Cognitive Assessment (Nasreddine et al., 2005). Participants were compensated for their time and gave informed consent in compliance with a protocol approved by the Baycrest Centre Research Ethics Committee.

2.2. Stimulus vowel continuum

A synthetic 5-step vowel continuum (hereafter vw1-5) was constructed such that each token would differ minimally acoustically, yet be perceived categorically (Bidelman et al., 2013; Pisoni, 1973). This was accomplished by parameterizing a single acoustic dimension across the stimuli, namely first formant frequency (F1). Each token was 100 ms in duration and included 10-ms of rise and fall time to reduce spectral splatter associated with abrupt sound onsets. Tokens contained identical voice fundamental (F0), second (F2), and third formant (F3) frequencies (F0: 100, F2: 1090, and F3: 2350 Hz, respectively) chosen to match prototypical productions from male speakers (Peterson and Barney, 1952). First, formant (F1) was varied parametrically over five equal steps between 430 and 730 Hz; the resultant stimulus set spanned a perceptual phonetic continuum from /u/ to /a/ (Bidelman et al., 2013). Stimuli were synthesized using a cascade formant synthesizer implemented in MATLAB (Klatt, 1980). It should be emphasized that the sole cue for speech perception in our task, namely F1 formant, falls within the frequency range of our audiometric screening and older adults' average PTAs. This, along with equal SL presentation, minimized the potential that age-related high-frequency hearing loss (i.e., >1000 Hz) might have affected the behavioral and ERP measures of interest. Acoustic spectrograms of the stimulus continuum are shown in Fig. 2.

2.3. Data acquisition and preprocessing

Data acquisition and response evaluation were similar to previous reports from our laboratory (Bidelman et al., 2013). Stimulus presentation was controlled by MATLAB (The MathWorks, Natick, MA, USA) routed to an audiometer (GSI) via a TDT RP2 interface (Tucker-Davis Technologies, Alachua, FL, USA) and delivered binaurally at an intensity of 83 dB SPL through insert earphones (ER-3A, Etymotic Research, Elk Grove, IL, USA). For older adults, intensity was adjusted to account for air-conduction hearing thresholds (PTAs) outside of normal limits (Ross et al., 2007). Presentation level was increased by +5 dB gain for each −5 dB of hearing loss greater than 15 dB HL (i.e., the mean threshold of younger adults). This level correction help ensure that stimuli were presented at roughly equal sensation level (SL) for both groups (~70 dB SL). It also helped rule out the possibility that group ERP effects might simply reflect differences in audibility. It should be noted that even when SL is equated, this may not take into account other distortions which emerge with hearing loss, for example, broadened auditory filters and loudness recruitment (He et al., 1998; Moore, 1996).

Extended acoustic tubing (50 cm) was used to eliminate electromagnetic stimulus artifact from contaminating neurophysiological responses (Aiken and Picton, 2008; Campbell et al., 2012). The effectiveness of this control was confirmed by the absence of an

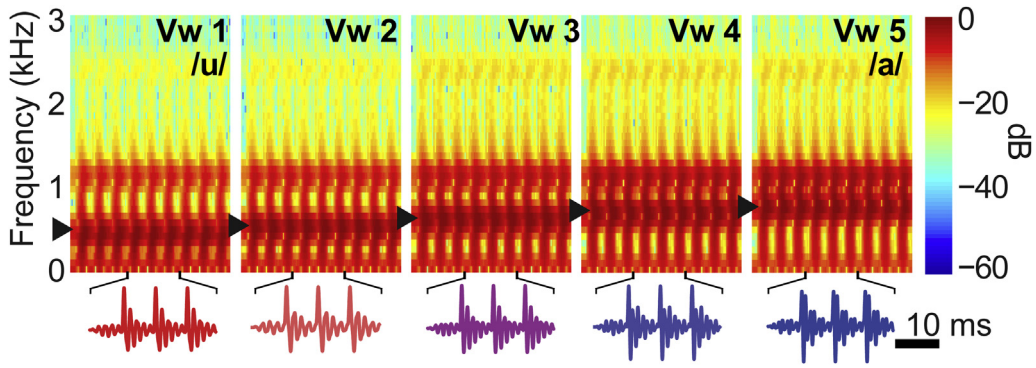

Fig. 2. Speech vowel continuum used to probe the categorical perception of speech. Panels show the spectrograms of the individual tokens; bottom insets show 3 periods of the individual time waveforms. First formant frequency was parameterized over 5 equal steps between 430 and 730 Hz (arrows) such that the resultant stimulus set spanned a perceptual phonetic continuum from /u/ to /a/.

artifact (and brainstem response) during a control run in which the air tubes were blocked to the ear.

During ERP recording, listeners heard 200 randomly ordered exemplars of each token and were asked to label them with a binary response as quickly as possible ("u" or "a"). Following the participant's behavioral response, the ISI was jittered randomly between 400 and 600 ms (20-ms steps, rectangular distribution). An additional 2000 trials (ISI = 150 ms) were then collected to measure the sub-microvolt brainstem ERPs (Bidelman and Krishnan, 2010; Bidelman et al., 2013). Brainstem ERPs show high repeatability within and robust stability across test sessions (Song et al., 2011) and are unaffected by attention (Galbraith and Kane, 1993; Hillyard and Picton, 1979; Picton et al., 1971). Thus, participants watched a self-selected movie with subtitles during blocks of brainstem recordings to facilitate a calm yet wakeful state. In total, the experimental protocol lasted ~2 hours.

The continuous EEG was recorded differentially between an electrode placed on the high forehead at the hairline referenced to linked mastoids. This montage is optimal for recording evoked responses of both subcortical and cortical origin (Bidelman et al., 2013; Krishnan et al., 2012; Musacchia et al., 2008). Contact impedances were maintained below 3 kΩ throughout the duration of the experiment. EEGs were digitized at 20 kHz and bandpass filtered online between 0.05 and 3500 Hz (SymAmps2, Compumedics Neuroscan, Charlotte, NC, USA). Traces were then segmented (cortical ERP: −100–600 ms; brainstem ERP: −40–210 ms), baselined to the pre-stimulus interval, and subsequently averaged in the time domain to obtain ERPs for each condition (Delorme and Makeig, 2004). Trials exceeding a ±50 μV threshold were rejected as blinks before averaging. Grand average evoked responses were then bandpass filtered in different frequency bands to highlight brainstem (80–2500 Hz) and cortical (1–30 Hz) ERPs, respectively (Bidelman et al., 2013; Krishnan et al., 2012; Musacchia et al., 2008).

2.4. Electrophysiological data analysis

2.4.1. Brainstem ERPs

Fast fourier transforms (FFTs) were computed from brainstem responses to index the magnitude of spectral information contained in each waveform. "Neural pitch salience" was then estimated from each spectrum using a harmonic template analysis whereby a series of sieves selected spectral activity at F0 and its integer multiples (Bidelman and Heinz, 2011; Bidelman and Krishnan, 2009). For quantifying pitch-relevant activity, this approach considers all response harmonics, and thus mimics the fact that perceptually, listeners combine information across harmonics to construct a unitary pitch percept (Gockel et al., 2007; Goldstein, 1973; Terhardt et al., 1982). The sieve was composed of 5 Hz wide bins situated at the F0 of our stimuli (100 Hz) and its integer multiples (i.e., 2F0, 3F0, 4F0, *n*F0; for *n*F0 < 1000 Hz). For each condition, the degree of pitch salience was estimated by dividing the mean density of activity falling within the sieve's bins by the mean density of activity in the whole FFT, providing a contrast between activity related to the voice pitch (i.e., F0) and background spectral energy unrelated to pitch. Although neural pitch salience was not expected to change across conditions (all stimuli had the same F0 frequency and amplitude), comparing this metric between groups allowed us to assess the effects of age on the neural encoding of voice pitch cues.

F1 magnitude was quantified from brainstem ERPs elicited by each of the five vowel stimuli. F1 reflects the primary cue used in the behavioral CP task and thus, provided us with a measure of how well brainstem transcribes this important feature of speech. F1 cannot be directly measured from response FFTs because their frequencies are not integer-related harmonics of the F0 (here, an integer multiple of 100 Hz). To this end, F1 magnitudes were instead quantified from each brainstem ERP as the amplitude of the responses' spectral envelope, computed via linear predictive coding (LPC) analysis (Bidelman et al., 2013). We computed a 35th-order LPC to obtain spectral envelopes of each brainstem responses and then measured F1 magnitude, recorded as the maximal spectral peak in the LPC between 400 and 750 Hz, that is, the expected F1 range from the input stimulus (Bidelman et al., 2013).

Onset latency was also estimated from each brainstem ERP by first cross-correlating each response time-waveform with the corresponding evoking stimulus (Galbraith and Brown, 1990). This provided a running correlation as a function of the lag between stimulus and response traces. The lag within a search window between 8 and 15 ms producing the maximum stimulus-to-response cross-correlation was taken as the onset latency for the brainstem response (Galbraith and Brown, 1990). The amplitude at this time sample was taken as magnitude of the response onset.

2.4.2. Neurophysiological noise

We measured the magnitude of inherent "brain noise" for each participant and condition using two approaches. First, we measured the mean RMS amplitude of the EEG in the combined pre- and post-stimulus intervals covering the time windows (−40 to 0 ms and 150–210 ms, respectively) (Fig. 4). These segments fall immediately before and after the time-locking stimulus event and have been assumed to contain only stochastic (i.e., spontaneous) neural activity (Anderson et al., 2012; Skoe et al., 2013a, 2013b). However, amplitudes within the ISI could instead reflect induced oscillatory brain activity not directly time-locked to the stimulus but nonetheless generated by the repeated presentation of the ongoing auditory stimulation (Shahin et al., 2009, 2010; Trainor et al., 2009). Thus, in addition to amplitude recorded within the ISI, we measured "neural noise" using a second, more veridical assay of spontaneous activity. In this alternate approach, RMS amplitude of the EEG was measured in a 100 ms window, 5 seconds before the start of any stimulus presentation. This allowed us to compare "neural noise" measured during stimulus presentation (which likely includes induced brain activity) and in participants' resting state before any experimental runs and auditory stimulation. Using a similar length analysis window in both cases ensured a fair comparison between the two measures of "neural noise" amplitude, which were not biased by differences in the duration of the analysis window.

2.4.3. Cortical ERPs

Peak amplitude and latency were measured for the prominent waves of the cortical ERPs (Pa, P1, N1, P2) at specific intervals. Pa was taken as the positivity between 25 and 35 ms, P1 as the positivity between 60 and 80 ms, N1 the negativity between 90 and 110 ms, and P2 as the positivity between 150 and 250 ms. The overall magnitude of the N1-P2 complex, computed as the voltage difference between the two individual waves, was used as an index of total cortical activation to each vowel.

2.5. Brain-behavior correlations and quantifying information transfer between brainstem and cortical speech responses

Pearson correlations were used to explore the correspondence between neurophysiological measures (brainstem: F1 amplitude; cortical: N1-P2 magnitude) as well as the link between these brain indices and behavioral speech identification performance. Pairwise correlations were also examined between hearing loss (pure-tone average) and neural measures to examine whether mild, age-related elevations in hearing sensitivity exerts differential effects dependent on the stage of speech processing (i.e., subcortical vs. cortical level).

To better understand the functional consequences of these correlations and speech information transfer between subcortical and cortical auditory structures, we examined the mutual information (MI) between ERP responses. We used MI (measured in bits) to quantify the degree of shared information (i.e., mutual dependence) between brainstem (BS) and cortical (C) speech responses. MI reflects the amount of information, or reduction in uncertainty, that knowing either signal provides about the other (Cover and Thomas, 1991). In the case of two time series (e.g., brainstem and cortical ERP), MI offers a means to detect both linear and nonlinear statistical dependencies between brain responses (correlations which measure only linear dependences) (Jeong et al., 2001). For the two evoked potential time series, MI was computed as:

$$MI(BS,C) = \sum_{bs,c} p(BS,C)\log_2\left[\frac{p(BS,C)}{p(BS)p(C)}\right] \quad (1)$$

where $p(BS,C)$ is the joint probability of BS and C, and $p(BS)$ and $p(C)$ are the marginal probabilities of signal BS and C, respectively. $p(BS)$ and $p(C)$ were estimated as the normalized distribution of amplitude values observed for the brainstem and cortical ERPs, respectively (for details of this derivation and its application to ERPs, Jeong et al., 2001). MI has been used previously to demonstrate that the dynamic coupling between cortical brain areas (i.e., interdependence) diminishes with age (Jeong et al., 2001; Ramanand et al., 2010). In the present context, MI was used to quantify the dependence or similarity between brainstem and cortical speech representations as measured via ERPs (Bidelman, in press; Garrett et al., 2013; Ramanand et al., 2010). This measure was used to quantify the redundancy in information between brainstem and cortical speech-evoked potentials (Chechik et al., 2006).

2.6. Behavioral data

Behavioral speech labeling speeds, that is, reaction times (RTs), were computed separately for each participant as the mean response latency across trials for a given speech token. Implausible RTs shorter than 200 ms or exceeding 1500 ms were discarded as outliers and excluded from further analysis (Bidelman et al., 2013). To obtain a single metric reflecting the efficiency of categorical speech processing, we computed a measure of perceptual "throughput", defined as identification accuracy (%) divided by RT (Salthouse and Hedden, 2002). In this ratio measure, a slower labeling speed penalizes the overall perceptual accuracy, and thus, reflects a listener's overall speech processing efficiency rather than only speed or accuracy alone (time-accuracy tradeoff) (Salthouse and Hedden, 2002). Differences in the slope of these psychometric functions (absolute values) were computed between the second and fourth vowel conditions to quantify the "steepness" of the categorical speech boundary between age cohorts (Bidelman et al., 2013).

3. Results

3.1. Behavioral speech identification performance

Behavioral performance for categorical speech processing, measured as perceptual throughput (accuracy/RT), is shown in Fig. 3. A repeated measures analysis of variance (ANOVA) with age (between subjects factor; 2 levels) and stimulus (within-subjects factor; 5 levels) revealed a significant age × stimulus interaction ($F_{4, 96} = 6.97$, $p = 0.003$). Post hoc contrasts indicated weaker behavioral performance in older relative to younger adults for vw 1-2, the exemplar /u/ tokens of the continuum. Separate analyses of identification and RT suggested this age-related effect on perceptual throughput was driven by older adults having prolonged RTs

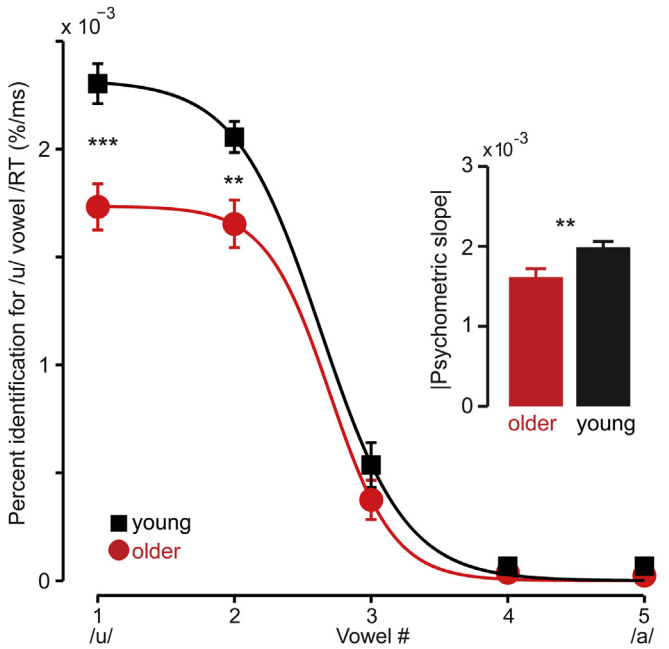

Fig. 3. Age-related differences in the perceptual classification of vowel sounds. Psychometric "throughput" for categorical speech processing defined as identification (%) (/u/ responses) divided by labeling reaction time (RT). Regardless of age, listeners hear a clear perceptual shift from /u/ to /a/ near the midpoint of the stimulus continuum (vw3). Age-related deficits in speech processing are evident for stimuli near the /u/ vowel exemplar in reduced processing efficiency for older adults. Slope of the psychometric functions (inset) reveal older adults have less pronounced categorical speech boundaries than younger listeners. Error bars denote ±1 s.e.m. ** $p < 0.01$, *** $p < 0.001$.

relative to younger adults across the board ($F_{1, 24} = 13.82$, $p = 0.001$); pure identification, that is, the proportion of trials identified as one vowel or the other, did not differ between groups ($F_{1, 24} = 0.01$, $p = 0.9$). Finally, analysis of the slope of the psychometric functions revealed that older adults had less pronounced categorical speech boundaries than younger listeners ($t_{24} = -2.93$, $p = 0.007$), suggesting a less dichotomous mapping of speech sound categories.

3.2. Electrophysiological responses

3.2.1. Brainstem ERPs

Speech-evoked brainstem responses are shown for young and older adults in Fig. 4. Raw time-waveforms and response spectra reveal more robust subcortical activity in younger relative to older adults and an age-related decline in neural phase-locking to the spectral details of speech. Age-related changes in brainstem speech encoding are most prominent in response spectra, which show weaker neural energy near the vowel F1, the sole cue for speech identification in our stimulus continuum. Older adults also demonstrated considerably weaker brainstem onsets (inset panel) indicating a reduced responsiveness to the transient cues of speech.

Brainstem response properties are shown in Fig. 5. An ANOVA on brainstem neural pitch salience revealed a main effect of age ($F_{1, 24} = 10.73$, $p = 0.003$). As expected by the static F0 of our stimuli, the main effect of stimulus type was not significant ($F_{4, 96} = 1.52$, $p = 0.202$) nor was the age × stimulus interaction ($F_{4, 96} = 0.29$, $p = 0.88$) (Fig. 5A). Critically, brainstem F1 magnitudes, reflecting the encoding of the defining speech formant cue, revealed an age × stimulus interaction ($F_{4, 96} = 2.51$, $p = 0.04$) (Fig. 5B). Planned comparisons revealed older adults had weaker encoding of vw2–4 relative to the younger cohort. Comparisons of brainstem response onset magnitude also indicated a significant age × stimulus interaction ($F_{4, 96} = 3.76$, $p =$

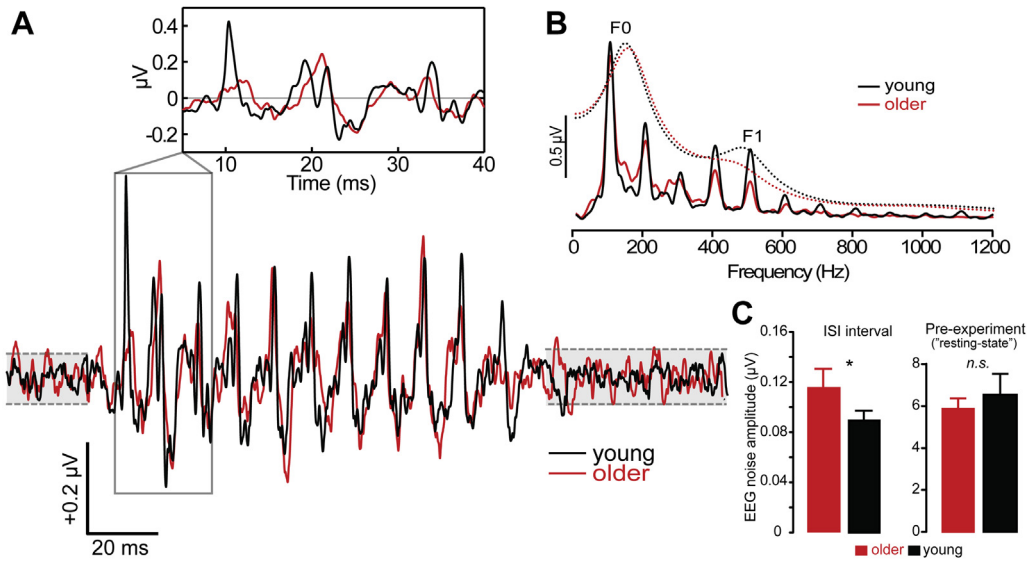

Fig. 4. Age-related changes in the subcortical response to speech. (A) Grand-average time waveforms reveal that younger adults have more robust and detailed subcortical responses than older adults indicating age-related deficits in neural phase-locking to spectral details of the speech. Age effects are prominent near the onset of the brainstem potential (~10–12 ms post stimulus) as indicated by the marked reduction in amplitude (inset). (B) Brainstem response spectra reveal that spectral details of the eliciting stimulus are less pronounced in older adults' neural encoding. Solid lines denote response FFTs; dotted lines, response spectral envelopes. Older adults show weaker sustained phase-locked responses to the stimulus F1 indicating reduced encoding of the cues necessary for speech recognition. (C) Older adults show increased "neural noise" between time-locked stimuli within the interstimulus interval (left; see shaded regions in A). However, no group differences are observed in spontaneous EEG activity measured before the start of the experiment (i.e., resting-state recording) (right) suggesting that older adults do not have more random and/or noisy EEG per se, but may have higher induced activation to speech (i.e., activity not directly time-locked to stimuli). Error bars = ±1 s.e.m. * $p < 0.05$. Abbreviations: EEG, electroencephalogram; F1, first formant frequency; FFTs, fast fourier transforms.

0.007) (Fig. 5C). These group differences were attributable to younger adults having stronger onset responses than the older cohort for vw1-2. No group differences were found in brainstem onset latency (Fig. 5D). Collectively, a significant interaction in F1 and onset coding suggests that aging distorts the normal pattern of speech encoding as found in younger adults.

3.2.2. Neural noise

Neurophysiological noise, measured as the mean EEG amplitude in the ISI windows, was used to quantify potential intrinsic differences in "brain noise" between age groups (Fig. 4C). An ANOVA on EEG noise showed a significant age × stimulus interaction ($F_{4, 96} = 2.83$, $p = 0.04$). Post hoc contrasts revealed this effect was because of older adults having larger ISI noise in the ambiguous speech condition (vw3) than younger adults. In stark contrast to measurements within ISIs, we found no differences in EEG amplitude before the start of the same stimulus condition (vw3), before auditory stimulation began (i.e., resting-state recording) ($t_{24} = 0.577$, $p = 0.56$)[1] Higher levels of activity during but not before stimulus presentation suggests that older adults may have increased induced brain responses during speech listening rather than increased spontaneous brain noise, per se (Skoe et al., 2013b).

3.2.3. Cortical ERPs

Fig. 6 shows speech-evoked cortical ERPs for younger and older adults. Consistent with previous studies (Godey et al., 2001), the early Pa and P1 waves of the cortical ERPs were poorly defined and showed considerable variability between listeners. This observation was confirmed by a lack of group difference in both Pa ($F_{1, 24} = 0.59$, $p = 0.80$) and P1 ($F_{1, 24} = 2.82$, $p = 0.10$) amplitudes. In contrast, prominent group differences emerged in the latency between the N1 and P2 deflections (~100–150 ms) (Fig. 6B). N1-P2 magnitudes showed a main effect of age ($F_{1, 24} = 8.07$, $p < 0.001$) and stimulus ($F_{4, 96} = 4.20$, $p = 0.003$) with no interaction ($F_{4, 96} = 0.81$, $p = 0.52$), indicating that older adults had stronger cortical activity to speech across the board. In both groups, the stimulus effect was attributable to the ambiguous vowel token (vw3) eliciting weaker responses than the exemplar vowel categories (vw1, vw5). A sole main effect of age was observed for N1 latency ($F_{1, 24} = 4.28$, $p = 0.049$), with no stimulus ($F_{4, 96} = 0.91$, $p = 0.46$) or age × stimulus interaction ($F_{4, 96} = 0.49$, $p = 0.74$). That is, older adults showed prolonged responses relative to younger adults across stimuli. P2 latency did not differ between groups ($F_{1, 24} = 0.19$, $p = 0.67$) but was modulated by the vowel stimulus ($F_{4, 96} = 3.85$, $p = 0.006$). As expected by the well-known frequency dependence of the auditory ERPs (Woods et al., 1993), the response to vw5 (highest F1) occurred with earlier latency than for the other stimuli.

3.2.4. Brain-behavior correlations and information transfer between brainstem and cortical speech representations

Collapsed across stimuli and groups, brainstem F1 magnitudes showed a positive correspondence with behavior (Pearson $r = 0.42$, $p < 0.05$). That is, more robust speech encoding at the level of the brainstem predicted better behavioral performance (Fig. 7A). A similarly strong but negative relationship was observed between cortical activity, as measured by N1-P2 magnitudes, and behavior ($r = -0.37$, $p < 0.05$) (Fig. 7B). The negative correlation indicates that greater cortical evoked activity (e.g., as found in older adults) is associated with poorer behavioral speech classification performance.

We observed a dissociation in the effects of age-related hearing loss on speech coding that depended on the functional level of auditory processing (brainstem vs. cortex) (Fig. 8). Greater hearing

[1] (on average, neural noise measured in the "resting state" recording was ~50× larger than when measured in the ISI periods [ISI windows: ~0.12 μV; preexperiment: ~6 μV]. Smaller EEG noise amplitudes in ISI compared with preexperiment recording is likely because of the fact that the former is obtained from the evoked response ERP [an average over N ≈ 2000 trials], and is filtered to remove low-frequency power inherent to the EEG. ERP noise improves proportional to √N. Thus, lower neural noise measured in the ISI is expected given time-domain averaging of multiple epochs. In addition, there was no specific task instruction during the preexperiment recordings so the larger amplitude in this time period may also reflect more participant movement and other artifacts [e.g., ocular activity]).

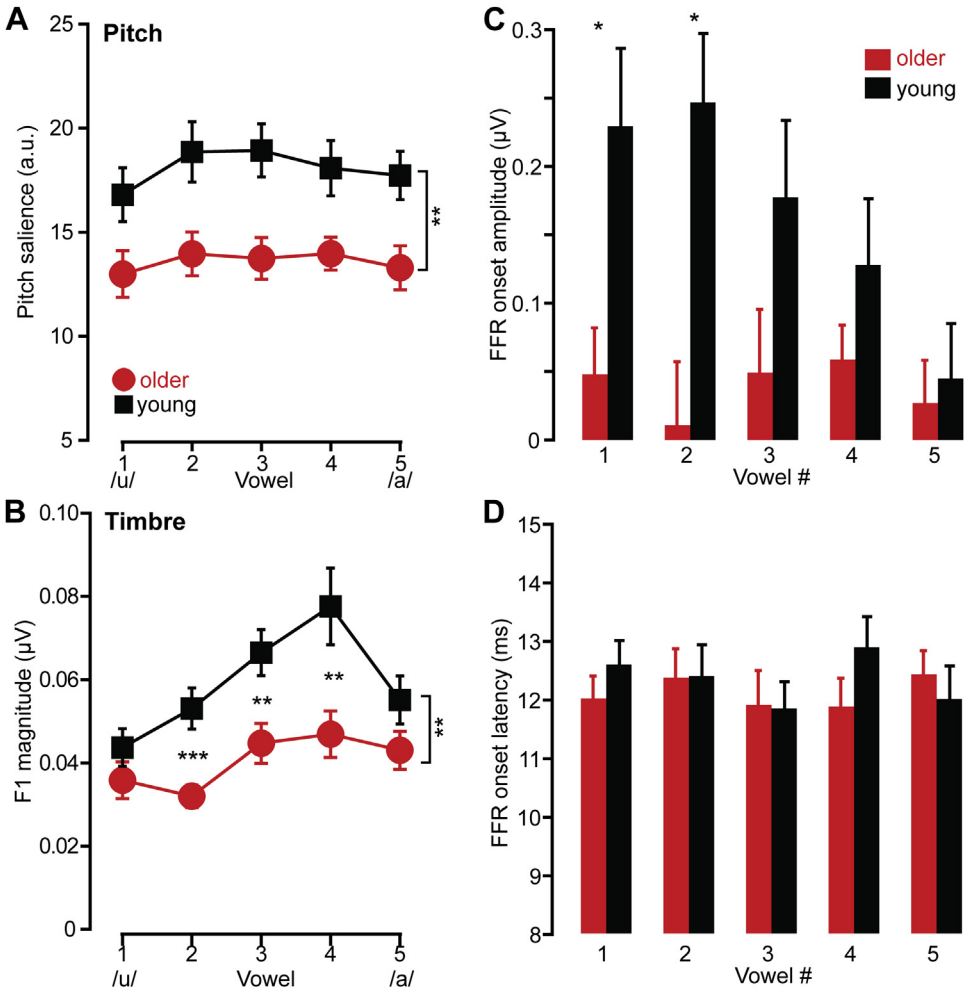

Fig. 5. Functional changes in brainstem speech encoding with normal aging. (A) Neural pitch salience (i.e., F0) and (B) F1 formant amplitudes extracted from brainstem frequency-following responses (FFRs) quantify the degree of voice pitch and timbre-related encoding in brainstem. Weaker pitch and timbre magnitudes are observed in older adults across the vowel continuum suggesting that age impairs the neural representations for prominent speech cues. (C–D) Onset responses reveal markedly weaker energy in older adults for the transitory response to speech. Error bars = ±1 s.e.m.; * $p < 0.05$.

loss in older adults was associated with weaker brainstem neural pitch salience ($r = -0.41$, $p < 0.001$) (Fig. 8A). Age, on the other hand, did not correlate with brainstem pitch encoding ($r = 0.03$, $p = 0.81$). As with F0 pitch salience, brainstem F1 encoding was associated with hearing loss ($r = -0.48$, $p < 0.05$) but not age ($r = 0.21$, $p = 0.09$) (not shown).

In contrast to brainstem, both hearing loss ($r = 0.54$, $p < 0.001$) and age ($r = 0.26$, $p < 0.038$) were associated with stronger cortical N1-P2 responses to speech (Fig. 8B). That is, older adults and those with more hearing impairment showed larger cortical speech-evoked ERPs. Age and hearing status could exert either independent influence or interact to affect cortical speech processing (Humes et al., 2012). However, age and hearing loss were only marginally correlated ($r = 0.23$, $p = 0.06$) providing evidence, though weak, that these factors act independently on older adults' speech processing. Nevertheless, given their marginal correspondence, we used partial correlations to tease apart the independent contribution of these two factors. Controlling for age, hearing loss remained a significant predictor of both brainstem pitch salience ($r = 0.51$, $p < 0.001$) and cortical ($r = -0.42$, $p < 0.001$) evoked response magnitudes. In summary, hearing loss was the main attribute, which predicted brainstem encoding of F0 and F1 speech cues, whereas both age and hearing loss were associated with cortical speech processing.

Pairwise correlations between neural and behavioral measures are shown in Fig. 9. Compared with younger adults, older listeners showed significant correspondences between the two brain measures as well as behavioral responses. In older (but not younger) listeners, brainstem F1 amplitudes were negatively associated with cortical N1-P2 magnitudes implying higher correspondence between brain representations across the auditory pathway. We confirmed this intuition using measures of information transfer between brainstem and cortex. MI (i.e., the degree of shared information) between brainstem and cortical ERP amplitudes was larger for older relative to younger adults as indicated by a main effect of age ($F_{1, 24} = 5.12$, $p = 0.033$) with no stimulus ($F_{4, 96} = 1.90$, $p = 0.12$) or age × stimulus interaction ($F_{4, 96} = 0.36$, $p = 0.83$) (Table 1)[2]

[2] (we also computed MI using the frequency spectra [i.e., FFT] of brainstem and cortical responses [brainstem ERP bandwidth: 80–2500 Hz; cortical ERP bandwidth: 1–30 Hz]. As expected based on the duality between time- and frequency-domains, spectral results were nearly identical to those obtained with response amplitude; MI computed between brainstem and cortical ERP spectra was larger for older relative to younger adults with a main effect of age [$F_{1, 24} = 6.15$, $p = 0.017$] but no stimulus [$F_{4, 96} = 1.49$, $p = 0.21$] or age × stimulus interaction [$F_{4, 96} = 0.88$, $p = 0.48$]. These results demonstrate a higher redundancy in older adult's neural activity to speech across the board when characterized either based on amplitude or spectral properties of auditory brain responses).

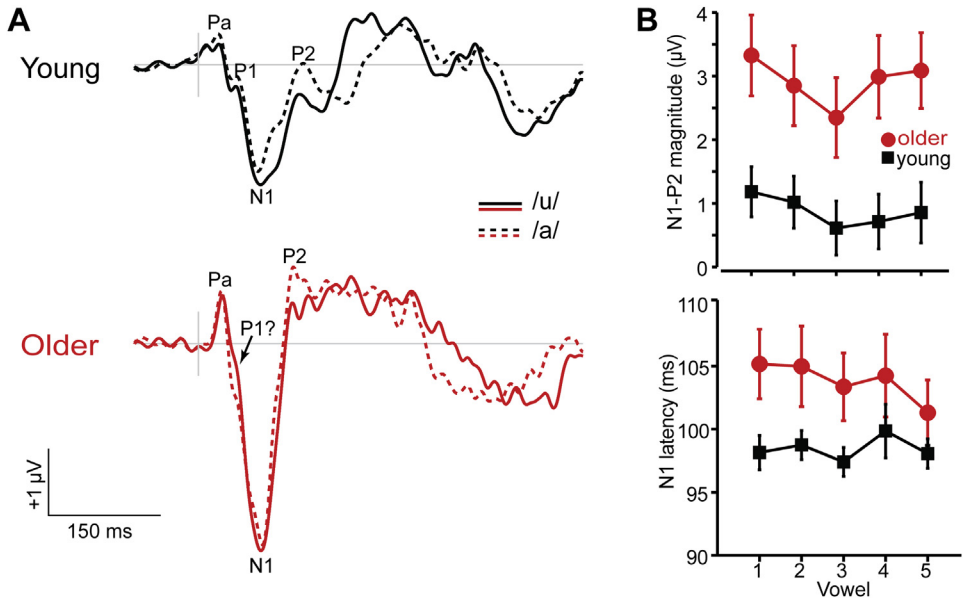

Fig. 6. Age-related changes in the cortical response to speech. (A) Cortical event-related potentials (ERPs) for younger and older listeners elicited by the prototypical vowel exemplars (vw1:/u/; vw5:/a/). Prominent waves of the cortical ERPs (e.g., N1 ~100 ms) are labeled. Gray vertical bars mark the time-locking stimulus. Note the distinct difference in response morphology between age groups beginning around the latency of N1 (~100 ms) and persisting through the P2 wave (~200 ms). (B) Functional changes in cortical ERP magnitude and latency with normal aging. Group N1-P2 magnitudes reveal overall weaker cortical activation to speech in older relative to younger adults across vowel stimuli. Similarly, N1 is prolonged in older adults suggesting less efficient processing of speech. Error bars = ±1 s.e.m.

Higher MI in the aging brain corroborates the increased correlations between neural measures and implies a greater redundancy in the information that is transferred between brainstem and auditory cortex during speech listening.

4. Discussion

Understanding the hierarchical operations of speech processing, and how normal aging affects its underlying representations along the auditory pathway requires comparing the output of the participating neural elements across multiple brain regions and timescales (Bidelman et al., 2013). By examining the connection between brainstem and cortical neuroelectric responses in both older and younger adults, we demonstrate a critical dissociation in how normal aging impacts speech processing and the transfer of information between different levels of the auditory pathway.

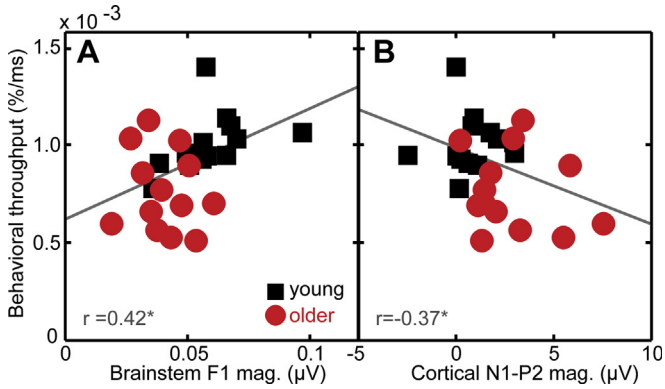

Fig. 7. Brain–behavior correlations. (A) Across groups, brainstem F1 magnitudes predict behavioral responses for speech sound classification. The positive relationship suggests that more robust subcortical encoding of speech cues corresponds with improved behavioral performance. (B) N1-P2 magnitudes of the ERPs predict behavioral responses. In contrast to the relationship between brainstem and behavior, a negative relationship between cortical activity and behavior indicates that larger responses in auditory cortical structures corresponds with poorer speech perception abilities. In both panels, each observation reflects the brain and behavioral response for an individual listener collapsed across stimulus conditions. * $p < 0.05$. Abbreviations: ERPs, event-related potentials; F1, first formant frequency.

4.1. Does aging increase neuronal noise in the nervous system?

Classical models of cognitive aging posit that older adults' poorer performance in behavioral tasks is attributable to an increased level of background noise in the aged brain, that is, the "neural noise" hypothesis (Hong and Rebec, 2012; Mireles and Charness, 2002; Salthouse and Lichty, 1985; Welford, 1981). The physiological basis of such noise is unknown. However, aging is associated with slower nerve conduction velocity (Peters, 2002) and decreased neural inhibition (Caspary et al., 2008). Thus, one possibility is that older adults' increased "neural noise" (if present) could be because of a compensatory escalation of neural firing to overcome age-related delays in neural transmission (Hong and Rebec, 2012). In the present study, we found increased neuroelectric activity in older adults EEG in the absence of auditory stimulation but only in the ISI between stimulus presentations (Fig. 4C); no age-related differences were observed in EEG amplitude before auditory stimulation, that is, during resting-state recordings. These findings suggest that older adults may not have inherent differences in stochastic brain activity per se. Rather, higher activity during the ISI suggests that age might increase the level of induced brain activity (likely high gamma oscillations of cortical origin; Pantev, 1995) not directly time-locked to speech but nonetheless evoked during continuous auditory presentation. Although evidence from modeling studies does suggest that the behavioral declines of aging can be simulated by progressively adding noise to relevant brain networks (Mireles and Charness, 2002), our data do not support the notion of increased "neural noise" in older adults (cf. Salthouse and Lichty, 1985; Welford,

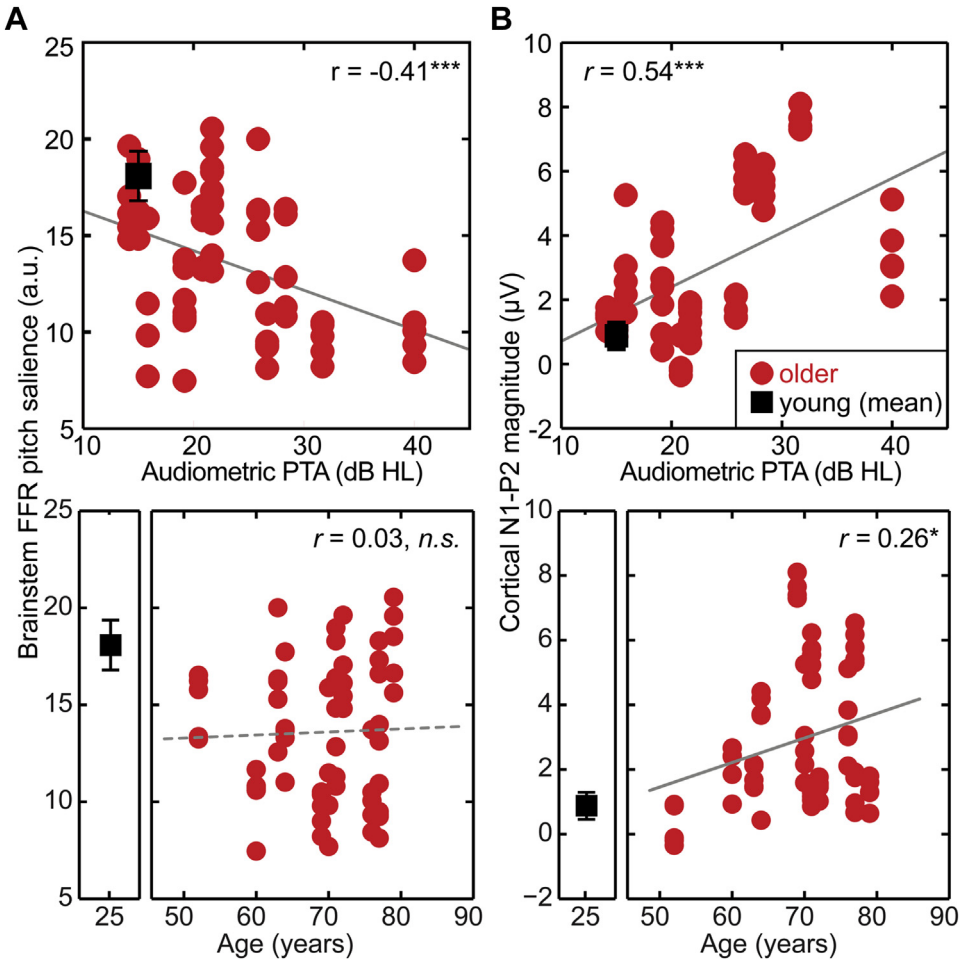

Fig. 8. Age and hearing loss yield dissociable effects on speech processing between subcortical and cortical levels. Effects of hearing loss (top panels) and age (bottom panels) on brainstem and cortical ERPs, A and B respectively. (A) Effects of age and hearing loss on brainstem responses. For older adults, responses to all five stimulus tokens are plotted against their individual hearing thresholds; all younger adults had thresholds better than 15 dB HL and thus, only the group mean is shown for the younger cohort. Older adults with mild hearing loss show weaker brainstem pitch salience for speech (top left). In contrast, age does not predict brainstem response magnitudes (bottom left). (B) Effects of age and hearing loss on cortical ERPs. Both hearing loss (top right) and age (bottom right) show positive correspondence with cortical N1-P2 magnitudes. The dissociation of age-related hearing loss on subcortical compared with cortical levels of speech processing suggests that normal aging yields reduced sensory excitation (brainstem) and increased dysinhibition (cortical) between functional stages of the central auditory nervous system. Solid lines denote significant correlations and dotted lines denote insignificant relationships. * $p < 0.05$; *** $p < 0.001$. Abbreviations: ERPs, event-related potentials; FFR, brainstem frequency-following response; PTA, puretone average.

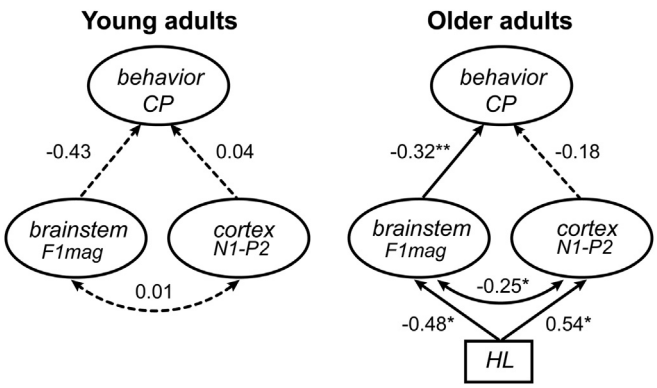

Fig. 9. Aging alters associations between brain and behavioral speech processing. Correlation structures between response measures are shown separately for each group. Brainstem and cortical ERPs are strongly correlated in older (but not younger) adults implying more redundancy in the transfer of information along the ascending auditory system. In older listeners, age-related hearing loss (HL) predicts both brainstem F1 and cortical speech encoding but in an inverse relationship. Significant correlations are denoted by solid lines; dotted lines = *n.s.* relationships. * $p < 0.05$, ** $p < 0.01$. Abbreviations: ERPs, event-related potentialscf; F1, first formant frequency.

1981). Instead, we find normal levels of spontaneous brain activity in the aging nervous system (with possibly increased induced activity) and more critically, an increased redundancy in the neurocomputations between levels of auditory processing (Fig. 9, Table 1; discussed in section 4.4). The meaning of induced brain activity is still a matter of debate and is outside the scope of the present evoked potential study. Nevertheless, animal studies have reported hyperexcitability and spontaneous activity in neurons of the dorsal cochlear nucleus in aged rats (Caspary et al., 2006). Thus, future work is needed to determine how these findings might scale to

Table 1
Mutual information (mean, SD) between brainstem and cortical speech representations

	Vowel stimulus				
	VW1	VW2	VW3	VW4	VW5
MI (bits)					
Younger adults	2.79 (0.24)	2.90 (0.27)	2.74 (0.32)	2.84 (0.24)	2.81 (0.29)
Older adults	3.01 (0.15)	3.02 (0.23)	2.93 (0.24)	2.97 (0.20)	2.99 (0.19)

Key: MI, mutual information; SD, standard deviation.

aged humans and the macro "neural noise" potentially recordable via EEG.

Our confirmation of a group difference for ISI amplitude measures but not resting-state recordings suggests a need to qualify recent suggestions of between-group differences in "neural noise." Using the less veridical ISI noise amplitude measures, recent studies have reported apparent increased "spontaneous activity" as a function of age (Anderson et al., 2012; Skoe et al., 2013b). Similar studies have further suggested an increase in EEG noise in socioeconomically deprived children, interpreted as demonstrating a "weaker, more variable" and "inefficient auditory system" resulting from an impoverished auditory environment during the formative years of childhood (Skoe et al., 2013a, p. 17,221). Our data and comparison of different "neural noise" measures do not support these conclusions. Rather, they suggest that amplitude measures in the ISI during continuous auditory stimulation, as observed in prior studies, most probably reflects induced rather than spontaneous brain activity. While age may not change spontaneous brain activity to an appreciable degree, our MI and correlational findings do imply an increased redundancy in neural representation across the auditory pathway. Our results therefore contrast the "neural noise hypothesis" of aging (Salthouse and Lichty, 1985). Instead, they are more consistent with the notion that aging reduces the complexity and functional flexibility in the brain's information channels (Garrett et al., 2013). Reduced functional flexibility may account for older adults' poorer behavioral performance in speech reception observed here and in previous studies (Gordon-Salant and Fitzgibbons, 1993; Hutka et al., 2013; Schneider et al., 2002; Strouse et al., 1998).

4.2. Age-related changes in the hierarchy of neurophysiological speech processing

4.2.1. Behavioral speech classification deficits

Behavioral studies have established that aging impairs the ability to discriminate rapid temporal features of complex sounds (Bergeson et al., 2001; Hutka et al., 2013; Schneider and Hamstra, 1999). Yet, effective speech communication depends on more than perceptual acuity; it requires that a listener extract and map continuous acoustic information to stored, discrete phonetic templates, a process exemplified in CP (Bidelman et al., 2013; Pisoni and Luce, 1987). Our study provides new evidence to suggest that aging impairs the brain's ability to perform this level of linguistic abstraction. When categorizing speech, older adults showed less dichotomous psychometric boundaries than their younger counterparts (Fig. 3), implying a reduced sensitivity and distortion of the phonetic categories of speech. Age-related changes in perceptual categorization have been observed across sensory modalities including audition (Strouse et al., 1998), vision (Kiffel et al., 2005), and olfaction (Suzuki et al., 2001). A plausible explanation for these diverse findings is that aging weakens the internalized neural representation for perceptual objects and thus, blurs the distinction between adjacent categories. In the context of speech listening, weaker, more variable templates for perceptual objects would tend to supply a less definitive decision rule during behavioral classification. Importantly, older adults' poorer CP for speech persisted despite controls for audibility (equal SL stimuli) and cognitive function (normal Montreal Cognitive Assessment scores). We cannot, however, rule out the possibility that other auditory distortions that arise with age and/or hearing loss (e.g., broadened auditory filters, loudness recruitment) (He et al., 1998; Moore, 1996) also contribute to our results. Nevertheless, our findings argue that age-related speech deficits can arise without significant peripheral or cognitive deficits (Humes, 1996; Plomp, 1986). We suggest that older adults may have an impoverished sensory processing and transmission of speech information within the central auditory nervous system (Schneider et al., 2002).

4.2.2. Sensory declines in brainstem speech processing

Corroborating behavioral measures, we found aging was associated with weaker speech encoding at the level of the brainstem. Older adults' responses showed less faithful transcription of important speech acoustics as evident by their decreased phase locking to voice pitch (F0) and timbre (F1 formant) cues as well as a weaker onset to the speech signal (Figs. 4 and 5). It is plausible that a weaker, less robust signal representation in lower-level brainstem structures feeds cortical mechanisms an impoverished representation of the acoustic speech waveform. Operating on lower-fidelity input, later decision processes would tend to show more variable encoding and lower signal-to-noise ratio. Lower signal-to-noise ratio in the phonetic templates for speech would lead to increased uncertainty in signal detection, providing less evidence upon which to base a behavioral decision. Indeed, across age groups, behavioral speech identification performance was well predicted by the degree to which F1-formant cues were captured in brainstem potentials (Fig. 7A); weaker subcortical representation for this defining speech cue was associated with slower, more variable, and less dichotomous speech identification performance. Whereas the present study did not control for potential differences in motor activity between groups, the more delayed early cortical auditory responses in older adults (Fig. 6B) suggest that in addition to any age-related motor slowing, perceptual processing is also delayed in older listeners. Slower perceptual stimulus encoding coupled with delayed motor timing is likely to contribute to older adult's weaker, more variable speech identification observed in the present study.

Older adults' reduced brainstem encoding of spectral information converges with recent electrophysiological reports identifying a deficit in fine-structure processing with increasing age (Clinard and Tremblay, 2013; Clinard et al., 2010; Grose and Mamo, 2012; Marmel et al., 2013). Age-related changes in both brainstem response synchrony and perceptual pitch discrimination abilities have been shown to decline with age independent of hearing loss (Clinard and Tremblay, 2013; Clinard et al., 2010; Marmel et al., 2013). These findings are consistent with older adults' reduced neural encoding of spectral pitch (F0) and timbre (F1) speech cues observed in the present study and their concomitant deficit in behavioral speech classification performance. Taken together, our results suggest that age-related distortions in early sensory auditory processing (i.e., those operating within 50 ms of stimulus onset) may negatively impact behaviors occurring some hundreds of milliseconds later.

Our findings also corroborate recent suggestions that age impairs central auditory processing, particularly in the "precision" with which subcortical structures encode complex speech sounds (Anderson et al., 2012; Parbery-Clark et al., 2012; Vander Werff and Burns, 2011). Weakened temporal phase-locking to rapid amplitude modulations have also been observed in near- and far-field recordings in animal models of aging (Parthasarathy et al., 2010; Parthasarathy and Bartlett, 2011, 2012) and are thus consistent with the present data in humans. Unfortunately, conclusions of previous human brainstem studies have been drawn using only a single speech token in the absence of a linguistic task making the functional consequences of older adults' weakened neural responses unclear. Weakened scalp-recorded brainstem activity could, for example, result simply from diminished gray matter volume (i.e., atrophy of neural tissue) and increased skull thickness known to accompany normal aging

and hearing loss (Albert et al., 2007; Eckert et al., 2012; Lin et al., 2014; Salat et al., 2004; Zhou et al., 2013). Our use of a continuum of stimuli along with a higher-order linguistic CP task reveals that aging interacts with the neural encoding of speech (Fig. 5B and C). Critically, this stimulus × group interaction demonstrates that in addition to previously observed sensory declines in brainstem speech processing, aging distorts the normal profile of speech representations. An inability to properly encode the rapid transient and sustained features of speech is thought to underlie at least some of the difficulties with speech reception observed in elderly individuals (Schneider and Hamstra, 1999; Strouse et al., 1998). In light of our findings and those of previous studies (Anderson et al., 2012; Clinard and Tremblay, 2013; Marmel et al., 2013; Parbery-Clark et al., 2012), it is possible that at least some of the older adults' receptive speech difficulties emerge as a result of deficient and distorted auditory encoding at pre-attentive, subcortical stages of speech processing. This proposition also supports the recent suggestion that progressive age-related declines in at least some high-order cognitive abilities (e.g., speech and/or language comprehension) might be initiated by age-related deterioration in early sensory mechanisms (Humes et al., 2013).

4.2.3. Cortical speech processing

Age-related changes were also observed in the cortical ERPs but with an opposite pattern from that observed in brainstem responses. Consistent with previous reports (Alain and Snyder, 2008; Snyder and Alain, 2005; Tremblay et al., 2003; Woods and Clayworth, 1986; Zendel and Alain, 2014), normal aging was associated with an increase and prolongation of the sensory components of the cortical evoked response (N1-P2) (Fig. 6). These waves are thought to reflect neural activation generated from thalamocortical pathways and the early auditory cortices (McGee et al., 1991; Scherg & von Cramon, 1986). However, it is important to note that early cortical responses may also be influenced by distal cortical regions, that is, "top-down" modulations (Hillyard and Picton, 1979). Enhanced amplitude in these earlier components nevertheless suggests that the aging process might act to overemphasize stimulus-relevant information that is supplied to the auditory cortices—perhaps from the weakened output of subcortical structures (Fig. 5). Such exaggerated representation of speech information may result from age-related declines in neural inhibition (Caspary et al., 2008; Parthasarathy and Bartlett, 2011; Parthasarathy et al., 2010) and/or de-afferentation (Kujawa and Liberman, 2006; Makary et al., 2011) within the central nervous system. In animal models, gradual downregulation of inhibitory neurotransmitter (e.g., GABA) occurs within various auditory nuclei with advancing age (Caspary et al., 2008). Such microscopic changes in central inhibition may account for the macroscopic increases in human cortical ERP activity observed here and in previous studies (Alain and Snyder, 2008; Alain and Woods, 1999; Snyder and Alain, 2005; Tremblay et al., 2003; Woods and Clayworth, 1986; Zendel and Alain, 2014). Parsimoniously, decreased inhibition may also account for older adults' reduced subcortical responses as well. Robust brainstem phase locking requires a precise interplay between excitatory and inhibitory processing (Parthasarathy and Bartlett, 2011). If one of these mechanisms is interrupted by aging, this would tend to increase the "jitter" in temporal processing, leading to blurrier and weakened brainstem responses in older listeners (Fig. 4).

Alternatively, increased cortical responsiveness may result from distal "top-down" (rather than local and/or "bottom-up") changes to inhibitory function mediated by non-auditory brain regions. Lesions to the prefrontal cortices are known to enhance the early auditory ERPs including the P1 and N1 response (Chao and Knight, 1997; Knight et al., 1999). By this account, declines in top-down modulation from prefrontal regions may diminish the normal "gating" of sensory input to the auditory cortices in a compensatory fashion (Peelle et al., 2011). Indeed, the exaggerated cortical ERPs observed herein may also arise because of the increased listening effort required of older listeners (Gosselin and Gagne, 2011). Our data cannot speak to whether older adults neurophysiological (brainstem and cortical ERPs) and behavioral speech processing deficits are the consequence of "bottom-up" or "top-down" influences. Changes in neural processing as early as the brainstem could reflect age-related changes local to the brainstem (Bajo et al., 2010; Gao and Suga, 1998; Yan et al., 2005), the influence of top-down modulation from cortical efferent projections (Suga et al., 2000; Tzounopoulos and Kraus, 2009), or more probably, a parallel decline in these two mechanisms in tandem (Xiong et al., 2009). Local reorganization or loss of network inhibition may underlie the relatively slower, more exaggerated cortical responses to speech observed in our older cohort.

4.3. Dissociable effects of age-related hearing loss on brainstem versus cortical speech processing

Behavioral and electrophysiological deficits observed in our aging cohort occurred in the absence of substantial hearing impairment. Though most (85%) of our elderly participants showed clinically normal hearing (PTAs $\leq$ 25 dB HL), slightly elevated thresholds in some ears relative to younger adults suggest classic signs of age-related presbycusis (Gates et al., 1990). We found that mild presbycusis was associated with changes in speech encoding at both subcortical and cortical levels of auditory processing but in entirely opposite ways (Figs. 8 and 9). Brainstem responses were weaker and cortical responses stronger in older adults with mildly poorer hearing. Critically, these effects were not driven solely by audibility, as stimulus sensational level was equated between age groups. Instead, our data provide evidence that even mild decline in peripheral hearing (1) weakens the early sensory transcription of speech at a subcortical level but (2) overemphasizes speech representations in cerebral structures, that is, there is a disproportionate amount of neural activation. These functional changes may result from decreased excitation and increased inhibition in brainstem (Parthasarathy and Bartlett, 2012) as compared with cortical (Caspary et al., 2008; Chao and Knight, 1997) structures, respectively.

We infer that even mild age-related hearing loss alters central auditory function. This notion is consistent with the observation that normal age-related presbycusis (i.e., elevated high-frequency hearing thresholds) is associated with reduced gray matter volume of auditory cortical regions (Eckert et al., 2012; Lin et al., 2014). However, our data further suggest that presbycusis might yield differential changes between lower- and higher-levels of the auditory pathway. The observed over-recruitment of processing from subcortical to cortical aspects of the speech network is consistent with the notion that with advancing age, additional brain mechanisms are allocated to compensate for degraded sensory input and aid spoken language comprehension (Peelle et al., 2011; Wong et al., 2010).

Specific effects of age and accompanying hearing loss are often difficult to parse given that these variables nearly always covary with one another (Humes, 1996) and with cognitive function (Humes et al., 2013). In the present study, we observed an insignificant (but marginal) relationship between age and hearing sensitivity suggesting that these two factors might contribute independently to older adults' speech listening deficits. In previous studies, abnormal auditory ERPs have been observed in older individuals with normal audiometric thresholds (Tremblay et al.,

2002, 2003) but not in younger adults with hearing impairment (Oates et al., 2002). These findings support the proposition that age and hearing loss can exert independent influence on speech processing. In agreement with this proposition, we found that multiple factors including hearing loss and age predicted neurophysiological as well as behavioral speech processing measures (Figs. 8 and 9), but did so relatively independently. Our findings thus converge with previous brainstem and cortical ERP studies which have shown independent contributions of age, hearing impairment, and central neurophysiological function on complex listening abilities (speech perception: Tremblay et al., 2003; Clinard and Tremblay, 2013; pitch discrimination: Marmel et al., 2013). We further extend these results and suggest that age and hearing status might have a differential impact on the neural processing of speech across the auditory pathway. Hearing loss was correlated with more neural response measures than age and was a strong predictor of brainstem responses to multiple speech cues (F0 pitch salience and F1) as well as the cortical ERPs. Age on the other hand, correlated only with cortical N1-P2 responses; it did not predict brainstem F0 pitch salience or F1 responses. These findings suggest that age alone might play a less dominant role in determining speech processing at lower (brainstem) relative to higher (cortical) levels of processing within the auditory system. Further work is needed to explore this possibility.

Our results broadly agree with recent studies examining brainstem responses to complex sounds, which demonstrate that age and hearing loss yield independent contributions to the subcortical encoding of acoustic information (Anderson et al., 2012; Clinard et al., 2010; Marmel et al., 2013). Studies which have partialed out the effects of hearing loss (Marmel et al., 2013) or considered only older adults with exceptional hearing (better than $\leq$20–25 dBHL between 0.5 and 8 kHz) (Anderson et al., 2012; Clinard et al., 2010) have shown reduced amplitude, phase-coherence (temporal precision), and delayed timing in neural phase-locking as measured via brainstem responses to tonal and speech stimuli. Recently, Vander Werff and Burns (2011) reported differences in sustained phase locking of the speech-evoked brainstem response between younger and older adults. However, once peripheral hearing status was taken into account, age-related effects were largely eradicated. Marmel et al. (2013), on the other hand, implicate age, but not absolute hearing thresholds, as the driving factor behind the strength of brainstem responses. The equivocal nature of age and hearing on brainstem encoding could be attributable to differences in stimuli between studies and the complexity of neural processing that is recruited in each case.

For example, it is possible that hearing loss might exert a larger effect on neural processing of more spectrotemporally complex sounds such as speech, as used here (Plyler and Ananthanarayan, 2001; Vander Werff and Burns, 2010). Acoustically rich stimuli require cross-frequency channel computations (Heinz et al., 2010) and thus, may stress brainstem encoding of spectral information in ways that simple pure-tones may not (Clinard et al., 2010; Marmel et al., 2013). This may explain why we see a large effect of even mild hearing loss on brainstem responses to speech—a complex signal, where other studies examining pure tones have not (Marmel et al., 2013).

The weak connection between hearing loss, neural processing, and behavior for simplistic acoustic stimuli are evident in animal lesion data. With sparse survival of the auditory nerve ($<$50% of all fibers), animals are capable of maintaining normal audiometric thresholds (Schuknecht and Woellner, 1955). This suggests that very limited neuronal mechanisms are required to offer robust behavioral acuity for simple stimuli (detecting tones in quiet). In addition to elevating thresholds, hearing impairment also negatively impacts other aspects of audition that would be relevant to the processing of spectrally complex signals include broadening the auditory filters and inducing loudness recruitment (He et al., 1998; Moore, 1996). Such distortions may also partially account for our finding that hearing loss remains a significant predictor of speech encoding at the level of the brainstem even after adjusting for audibility.

It is conceivable that neural degeneration at the level of the auditory nerve or more central sites may partially explain some of our age-related findings. Recent postmortem estimates of neural survival indicate that in humans, auditory nerve fibers degenerate with advancing age on the order of 100 spiral ganglion cells per year of life (Makary et al., 2011). Such age-related de-afferentation occurs without cochlear hair cell loss, suggesting that neuronal fiber counts decline in the absence of traumatic noise exposure or loss of sensory receptors, that is, true age-related neural loss. Decreased peripheral neural integrity may distort and/or diminish initial speech representations supplied to the brain. This may in turn impair the ability to distinguish the rapid transient spectrotemporal features of sound relevant to the perception of speech (Hood, 1998). Our older adults also had relatively normal PTAs but nevertheless showed signs of high-frequency presbycusis above 2 kHz (Fig. 1). Thus, while the relevant speech cues (e.g., F0, F1) were within the range of hearing and were adjusted for audibility (i.e., sensation level), it remains possible that losses in high-frequency neurons affected low-frequency stimulus encoding. Single-unit recordings in animal models demonstrate that hearing impairment (induced by noise) creates a hypersensitive "tail" in auditory nerve fiber tuning curves (Liberman and Dodds, 1984). As a result, high-frequency neurons can become more responsive to low-frequency stimulation and amplitude modulations (i.e., stimulus envelope) with hearing loss (Kale and Heinz, 2010). By this account, we might have expected more robust encoding of F0 (i.e., the speech envelope) in our older relative to younger cohort. However, this is opposite of what we observed; older adults had weaker F0 encoding than younger adults (Fig. 5A). Thus, while age- or hearing-related neural degeneration and low-frequency recruitment in high-frequency fibers is possible, it is unlikely to account for the entirety of our results, particularly the differences observed in cortical responses.

It is also possible that some older adults in our study had some amount of conductive, rather than sensorineural hearing loss. Bone-conduction hearing thresholds would be needed to rule out this possibility. Previous ERP studies have shown that the effect of conductive hearing impairment is a reduction in audibility (signal attenuation), which manifests in smaller amplitude and prolonged latencies of the auditory evoked potentials (Hall, 1992, pp. 355–357; Picton, 2010, p. 232). If older listeners' hearing loss was solely conductive, we would have expected delayed and weaker response amplitudes for brainstem and cortical ERPs across the board. Yet, we found differential group effects between each level of processing in terms of both latency and amplitude, which cannot be directly attributed to reduced audibility. More critically, a stimulus $\times$ group interaction observed for brainstem ERPs (Fig. 5C) indicates a more complex and/or distorted pattern of speech processing in older, relative to younger ears. Such a differential profile between older and younger adults cannot be explained solely by conductive impairment, which would have had only a uniform effect between groups. These findings suggest that when hearing loss was present in our older listeners, it most definitely contained a sensorineural component. While the specific etiology of older adults' peripheral hearing cannot be established using the noninvasive methods used herein, our data do reveal a striking dissociation in how age-related presbycusis alters speech processing from brainstem through cortical structures. Future studies are needed to better characterize the effects of specific hearing etiologies and hearing profiles on speech processing limited in this study.

Nevertheless, it must be emphasized that altered neural activity to speech observed in our older cohort is unlikely the result of a single influence alone. The line between peripheral and central function and/or impaired sensory encoding versus signal transmission is difficult to fully disentangle in this and previous studies (Marmel et al., 2013; Vander Werff and Burns, 2010). Further research is needed to fully clarify the roles of age and hearing loss on speech processing during aging. Although our data provide some evidence for an independence of these factors, speech reception difficulties in the elderly individuals are most likely the result of interactions between aging and hearing status. Indeed, recent meta-analyses conclude that the "…existence of 'central presbycusis' is a multifactorial condition that involves age- and/or disease-related changes in the auditory system and in the brain" (Humes et al., 2012, p. 636).

4.4. Over-redundant speech representations with age

We found higher correlational associations and mutual information between brainstem and cortical brain processing in older listeners (Fig. 9). Similar information traversing the auditory pathway suggests that neural processing of speech becomes more redundant with advancing age. As demonstrated in animal models, neural representations are typically reduced in redundancy between each successive stage of auditory processing (Chechik et al., 2006). We posit that the over-redundancy in older adults' speech activity reflects a breakdown of this normal pruning mechanism which leads to a distorted transfer of neural information. Increased commonality (i.e., decreased entropy) between brain-states increases across the life span and has been linked to decreased cognitive flexibility, less adaptability, and poorer perceptual skills (Garrett et al., 2013). It is possible that the more redundant neural signatures transferred along the aged brain revealed in our study account for at least some of the speech listening deficits that arise later in life. Alternatively, increased redundancy in older adults may represent a form of adaptive response to age and/or hearing loss through increased top-down modulation (Peelle et al., 2011; Wong et al., 2010). Under this interpretation, both the exaggerated cortical responsiveness and increased redundancy we observe in older adults' neural processing of speech may reflect a similar underlying mechanism brought about by (1) increased listening effort; (2) top-down compensation; (3) diminished "gating" of sensory input (Gosselin and Gagne, 2011; Peelle et al., 2011); or (4) a combination of these age-related factors. Future work should disambiguate these various interpretations.

5. Conclusion

The present study compared speech-evoked brainstem and cortical ERPs elicited in older and younger adults in response to a categorical speech sound continuum. Older adults showed weaker neural encoding for voice pitch and timbre cues of the speech signal at the level of the brainstem. Similarly, cortical potentials were magnified and delayed in older relative to younger listeners. Importantly, an interaction between age and stimulus encoding indicated that the normal pattern of speech processing observed in younger listeners is distorted with advancing age. Mutual information and correlations between brainstem and cortical responses were also higher in older adults without concomitant changes in spontaneous brain activity (i.e., "neural noise"). These findings indicate more redundancy in neural speech representations between functional levels of the auditory pathway. These neurobiological deficits were paralleled in behavior, as older adults showed poorer (i.e., less dichotomous and slower) categorical speech perception than their younger counterparts.

Both age and mild hearing loss contributed to the neural encoding of speech in brainstem and cerebral cortex but did so independently and differentially. Age and hearing independently predicted cortical speech processing whereas brainstem responses to speech cues (F0, F1) were predicted mainly by age-related presbycusis. Mild presbycusis was associated with weaker brainstem but larger cortical speech activity, suggesting reduced sensory encoding might be overcompensated by increased dysinhibition in cerebral cortex. Taken together, our results show that normal age-related changes in brain physiology may exert a differential effect on speech processing between subcortical and cortical levels of the auditory system. We infer that these age-related changes distort the hierarchy of speech representations along the auditory pathway, reduce neural flexibility in the speech network, and ultimately impair the acoustic-phonetic mapping necessary for robust speech understanding. The innovative electrophysiological approach used here provides important insight into the nature of neural representation and brainstem-cortical reciprocity in the aged brain that would be missed by recording only a single-isolated response.

Disclosure statement

The authors declare no personal or financial conflicts of interest.

Acknowledgements

The authors thank Yu He for assistance in setting up the experimental protocol. Portions of this research were supported by Canadian Institutes of Health Research (MOP 106619), the Natural Sciences and Engineering Research Council of Canada (grant number 194536) (Claude Alain), and the GRAMMY Foundation (Gavin M. Bidelman). Correspondence and requests for materials should be addressed to Gavin M. Bidelman (g.bidelman@memphis.edu).

References

Aiken, S.J., Picton, T.W., 2008. Envelope and spectral frequency-following responses to vowel sounds. Hear. Res. 245, 35–47.
Alain, C., Woods, D.L., 1999. Age-related changes in processing auditory stimuli during visual attention: evidence for deficits in inhibitory control and sensory memory. Psychol. Aging 14, 507–519.
Alain, C., Snyder, J.S., 2008. Age-related differences in auditory evoked responses during rapid perceptual learning. Clin. Neurophysiol. 119, 356–366.
Alain, C., McDonald, K., Van Roon, P., 2012. Effects of age and background noise on processing a mistuned harmonic in an otherwise periodic complex sound. Hear. Res. 283, 126–135.
Albert, A.M., Ricanek Jr., K., Patterson, E., 2007. A review of the literature on the aging adult skull and face: implications for forensic science research and applications. Forensic Sci. Int. 172, 1–9.
Anderson, S., Parbery-Clark, A., White-Schwoch, T., Kraus, N., 2012. Aging affects neural precision of speech encoding. J. Neurosci. 32, 14156–14164.
Bajo, V.M., Nodal, F.R., Moore, D.R., King, A.J., 2010. The descending corticocollicular pathway mediates learning-induced auditory plasticity. Nat. Neurosci. 13, 253–260.
Bergeson, T.R., Schneider, B.A., Hamstra, S.J., 2001. Duration discrimination in younger and older adults. Can. Acoust. 29, 3–10.
Bidelman, G.M. in press. Objective information-theoretic algorithm for detecting brainstem evoked responses to complex stimuli. J. Am. Acad. Audiol.
Bidelman, G.M., Krishnan, A., 2009. Neural correlates of consonance, dissonance, and the hierarchy of musical pitch in the human brainstem. J. Neurosci. 29, 13165–13171.
Bidelman, G.M., Krishnan, A., 2010. Effects of reverberation on brainstem representation of speech in musicians and non-musicians. Brain Res. 1355, 112–125.
Bidelman, G.M., Heinz, M.G., 2011. Auditory-nerve responses predict pitch attributes related to musical consonance-dissonance for normal and impaired hearing. J. Acoust. Soc. Am. 130.
Bidelman, G.M., Gandour, J.T., Krishnan, A., 2011. Cross-domain effects of music and language experience on the representation of pitch in the human auditory brainstem. J. Cogn. Neurosci. 23, 425–434.
Bidelman, G.M., Moreno, S., Alain, C., 2013. Tracing the emergence of categorical speech perception in the human auditory system. Neuroimage 79, 201–212.

Brandy, W.T., 2002. Speech audiometry. In: Katz, J. (Ed.), Handbook of Clinical Audiology. Lippincott Williams & Wilkins, Baltimore, MD, pp. 96–110.
Campbell, T., Kerlin, J.R., Bishop, C.W., Miller, L.M., 2012. Methods to eliminate stimulus transduction artifact from insert earphones during electroencephalography. Ear Hear. 33, 144–150.
Caspary, D.M., Hughes, L.F., Schatteman, T.A., Turner, J.G., 2006. Age-related changes in the response properties of cartwheel cells in rat dorsal cochlear nucleus. Hear. Res. 216, 207–215.
Caspary, D.M., Ling, L., Turner, J.G., Hughes, L.F., 2008. Inhibitory neurotransmission, plasticity and aging in the mammalian central auditory system. J. Exp. Biol. Med. 211, 1781–1791.
Chao, L.L., Knight, R.T., 1997. Prefrontal deficits in attention and inhibitory control with aging. Cereb. Cortex 7, 63–69.
Chechik, G., Anderson, M.J., Bar-Yosef, O., Young, E.D., Tishby, N., Nelken, I., 2006. Reduction of information redundancy in the ascending auditory pathway. Neuron 51, 359–368.
Chmiel, R., Jerger, J., 1996. Hearing aid use, central auditory disorder, and hearing handicap in elderly persons. J. Am. Acad. Audiol. 7, 190–202.
Clinard, C.G., Tremblay, K.L., 2013. Aging degrades the neural encoding of simple and complex sounds in the human brainstem. J. Am. Acad. Audiol. 24, 590–599.
Clinard, C.G., Tremblay, K.L., Krishnan, A.R., 2010. Aging alters the perception and physiological representation of frequency: evidence from human frequency-following response recordings. Hear. Res. 264, 48–55.
Cover, T.M., Thomas, J.A., 1991. Entropy, relative entropy and mutual information. Elem. Inf. Theor., 12–49.
Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics. J. Neurosci. Methods 134, 9–21.
Eckert, M.A., Cute, S.L., Vaden, K.I., Kuchinsky, S.E., Dubno, J.R., 2012. Auditory cortex signs of age-related hearing loss. J. Assoc. Res. Otolaryngol. 13, 703–713.
Galbraith, G.C., Brown, W.S., 1990. Cross-correlation and latency compensation analysis of click-evoked and frequency-following brain-stem responses in man. Electroencephalogr. Clin. Neurophysiol. 77, 295–308.
Galbraith, G.C., Kane, J.M., 1993. Brainstem frequency-following responses and cortical event-related potentials during attention. Percept. Mot. Skills 76, 1231–1241.
Gao, E., Suga, N., 1998. Experience-dependent corticofugal adjustment of midbrain frequency map in bat auditory system. Proc. Natl. Acad. Sci. U.S.A 95, 12663–12670.
Garrett, D.D., Samanez-Larkinc, G.R., MacDonaldd, S.W.S., Lindenberger, U., McIntosh, A.R., Grady, C.L., 2013. Moment-to-moment brain signal variability: a next frontier in human brain mapping? Neurosci. Biobehav. Rev. 37, 610–624.
Gates, G.A., Cooper, J.C., Kannel, W.B., Miller, N.J., 1990. Hearing in the elderly: the Framingham cohort, 1983-1985. Ear Hear. 11, 247–256.
Gockel, H.E., Moore, B.C., Carlyon, R.P., Plack, C.J., 2007. Effect of duration on the frequency discrimination of individual partials in a complex tone and on the discrimination of fundamental frequency. J. Acoust. Soc. Am. 121, 373–382.
Godey, B., Schwartz, D., de Graaf, J.B., Chauvel, P., Liégeois-Chauvel, C., 2001. Neuromagnetic source localization of auditory evoked fields and intracerebral evoked potentials: a comparison of data in the same patients. Clin. Neurophysiol. 112, 1850–1859.
Goldstein, J.L., 1973. An optimum processor theory for the central formation of the pitch of complex tones. J. Acoust. Soc. Am. 54, 1496–1516.
Gordon-Salant, S., Fitzgibbons, P.J., 1993. Temporal factors and speech recognition performance in young and elderly listeners. J. Speech Hear. Res. 36, 1276.
Gosselin, P.A., Gagne, J.P., 2011. Older adults expend more listening effort than young adults recognizing audiovisual speech in noise. Int. J. Audiol. 50, 786–792.
Grose, J.H., Mamo, S.K., 2012. Processing of temporal fine structure as a function of age. Ear Hear. 33, 187–194.
Hall, J.W., 1992. Handbook of Auditory Evoked Responses. Allyn and Bacon, Needham Heights.
He, N., Dubno, J.R., Mills, J.H., 1998. Frequency and intensity discrimination measured in a maximum-likelihood procedure from young and aged normal-hearing subjects. J. Acoust. Soc. Am. 103, 553–565.
Heinz, M.G., Swaminathan, J., Boley, J.D., Kale, S., 2010. Across-fiber coding of temporal fine-structure: effects of noise-induced hearing loss on auditory-nerve responses. In: Lopez-Poveda, E.A., Palmer, A.R., Meddis, R. (Eds.), The Neurophysiological Bases of Auditory Perception. Springer, New York, pp. 621–630.
Hillyard, S.A., Picton, T.W., 1979. Event-related brain potentials and selective information processing in man. In: Desmedt, J.E. (Ed.), Progress in Clinical Neurophysiology. Karger, Basel, pp. 1–52.
Hong, S.L., Rebec, G.V., 2012. A new perspective on behavioral inconsistency and neural noise in aging: compensatory speeding of neural communication. Front. Aging Neurosci. 4.
Hood, L.J., 1998. Auditory neuropathy: what is it and what can we do about it? Hearing J. 51, 10–18.
Humes, L.E., 1996. Speech understanding in the elderly. J. Am. Acad. Audiol. 7, 161–167.
Humes, L.E., Busey, T.A., Craig, J., Kewley-Port, D., 2013. Are age-related changes in cognitive function driven by age-related changes in sensory processing? Atten. Percept. Psychophys. 75, 508–524.
Humes, L.E., Dubno, J.R., Gordon-Salant, S., Lister, J.J., Cacace, A.T., Cruickshanks, K.J., Gates, G.A., Wilson, R.H., Wingfield, A., 2012. Central presbycusis: a review and evaluation of the evidence. J. Am. Acad. Audiol. 23, 635–666.
Hutka, S., Alain, C., Binns, M., Bidelman, G.M., 2013. Age-related differences in the sequential organization of speech sounds. J. Acoust. Soc. Am. 133, 4177–4187.
Jeong, J., Gore, J.C., Peterson, B.S., 2001. Mutual information analysis of the EEG in patients with Alzheimer's disease. Clin. Neurophysiol. 112, 827–835.
Kale, S., Heinz, M.G., 2010. Envelope coding in auditory nerve fibers following noise-induced hearing loss. J. Assoc. Res. Otolaryngol. 11, 657–673.
Kiffel, C., Campanella, S., Bruyer, R., 2005. Categorical perception of faces and facial expressions: the age factor. Exp. Aging Res. 31, 119–147.
Klatt, D.H., 1980. Software for a cascade/parallel formant synthesizer. J. Acoust. Soc. Am. 67, 971–995.
Knight, R.T., Richard Staines, W., Swick, D., Chao, L.L., 1999. Prefrontal cortex regulates inhibition and excitation in distributed neural networks. Acta Psychol. (Amst) 101, 159–178.
Konkle, D.F., Beasley, D.S., Bess, F.H., 1977. Intelligibility of time-altered speech in relation to chronological aging. J. Speech Hear. Res. 20, 108–115.
Krishnan, A., Gandour, J.T., Bidelman, G.M., 2010. The effects of tone language experience on pitch processing in the brainstem. J. Neurolinguistics 23, 81–95.
Krishnan, A., Bidelman, G.M., Smalt, C.J., Ananthakrishnan, S., Gandour, J.T., 2012. Relationship between brainstem, cortical and behavioral measures relevant to pitch salience in humans. Neuropsychologia 50, 2849–2859.
Kujawa, S.G., Liberman, M.C., 2006. Acceleration of age-related hearing loss by early noise exposure: evidence of a misspent youth. J. Neurosci. 26, 2115–2123.
Liberman, M.C., Dodds, L.W., 1984. Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations of threshold tuning curves. Hear. Res. 16, 55–74.
Lin, F.R., Ferrucci, L., An, Y., Goh, J.O., Doshi, J., Metter, E.J., Davatzikos, C., Kraut, M.A., Resnick, S.M., 2014. Association of hearing impairment with brain volume changes in older adults. Neuroimage 90, 84–92.
Makary, C.A., Shin, J., Kujawa, S.G., Liberman, M.C., Merchant, S.N., 2011. Age-related primary cochlear neuronal degeneration in human temporal bones. J. Assoc. Res. Otolaryngol. 12, 711–717.
Marmel, F., Linley, D., Carlyon, R.P., Gockel, H.E., Hopkins, K., Plack, C.J., 2013. Subcortical neural synchrony and absolute thresholds predict frequency discrimination independently. J. Assoc. Res. Otolaryngol. 14, 755–766.
McGee, T., Kraus, N., Comperatore, C., Nicol, T., 1991. Subcortical and cortical components of the MLR generating system. Brain Res. 544, 211–220.
Mireles, D.E., Charness, N., 2002. Computational explorations of the influence of structured knowledge on age-related cognitive decline. Psychol. Aging 17, 245–259.
Moore, B.C., 1996. Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. Ear Hear. 17, 133–161.
Musacchia, G., Strait, D., Kraus, N., 2008. Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and non-musicians. Hear. Res. 241, 34–42.
Nasreddine, Z.S., Phillips, N.A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J.L., Chertkow, H., 2005. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J. Am. Geriatr. Soc. 53, 695–699.
Oates, P.A., Kurtzberg, D., Stapells, D.R., 2002. Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound discrmination. Ear Hear. 23, 399–415.
Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113.
Pantev, C., 1995. Evoked and induced gamma-band activity of the human cortex. Brain Topogr. 7, 321–330.
Parbery-Clark, A., Anderson, S., Hittner, E., Kraus, N., 2012. Musical experience offsets age-related delays in neural timing. Neurobiol. Aging 33, 1483.e1–1483.e4.
Parthasarathy, A., Bartlett, E., 2011. Age-related auditory deficits in temporal processing in F-344 rats. Neuroscience 192, 619–630.
Parthasarathy, A., Bartlett, E., 2012. Two-channel recording of auditory-evoked potentials to detect age-related deficits in temporal processing. Hear. Res. 289, 52–62.
Parthasarathy, A., Cunningham, P.A., Bartlett, E.L., 2010. Age-related differences in auditory processing as assessed by amplitude-modulation following responses in quiet and in noise. Front. Aging Neurosci. 2, 152.
Peelle, J.E., Troiani, V., Grossman, M., Wingfield, A., 2011. Hearing loss in older adults affects neural systems supporting speech comprehension. J. Neurosci. 31, 12638–12643.
Peters, A., 2002. The effects of normal aging on myelin and nerve fibers: a review. J. Neurocytol. 31, 581–593.
Peterson, G.E., Barney, H.L., 1952. Control methods used in a study of vowels. J. Acoust. Soc. Am. 24, 175–184.
Picton, T.W., 2010. Human Auditory Evoked Potentials, first ed. Plural Publishing, San Diego.
Picton, T.W., Hillyard, S.A., Galambos, R., Schiff, M., 1971. Human auditory attention: a central or peripheral process? Science 173, 351–353.
Pisoni, D.B., 1973. Auditory and phonetic memory codes in the discrimination of consonants and vowels. Percept. Psychophys. 13, 253–260.
Pisoni, D.B., Luce, P.A., 1987. Acoustic-phonetic representations in word recognition. Cognition 25, 21–52.
Plomp, R., 1986. A signal-to-noise ratio model for the speech-reception threshold of the hearing impaired. J. Speech Hear. Res. 29, 146–154.
Plyler, P.N., Ananthanarayan, A.K., 2001. Human frequency-following responses: representation of second formant transitions in normal-hearing and hearing-impaired listeners. J. Am. Acad. Audiol. 12, 523–533.

Ramanand, P., Bruce, M.C., Bruce, E.N., 2010. Mutual information analysis of EEG signals indicates age-related changes in cortical interdependence during sleep in middle-aged versus elderly women. J. Clin. Neurophysiol. 27, 274–284.
Ricketts, T.A., Hornsby, B., 2005. Sound quality measures for speech in noise through a commercial hearing aid implementing "digital noise reduction". J. Am. Acad. Audiol. 16, 272–279.
Ross, B., Fujioka, T., Tremblay, K.L., Picton, T.W., 2007. Aging in binaural hearing begins in mid-life: evidence from cortical auditory-evoked responses to changes in interaural phase. J. Neurosci. 27, 11172–11178.
Salat, D.H., Buckner, R.L., Snyder, A.Z., Greve, D.N., Desikan, R.S., Busa, E., Morris, J.C., Dale, A.M., Fischl, B., 2004. Thinning of the cerebral cortex in aging. Cereb. Cortex 14, 721–730.
Salthouse, T.A., Lichty, W., 1985. Tests of the neural noise hypothesis of age-related cognitive change. J. Gerontol. 40, 443–450.
Salthouse, T.A., Hedden, T., 2002. Interpreting reaction time measures in between-group comparisons. J. Clin. Exp. Neuropsychol. 24, 858–872.
Scherg, M., von Cramon, D.Y., 1986. Evoked dipole source potentials of the human auditory cortex. Electroencephalogr. Clin. Neurophysiol. 65, 344–360.
Schneider, B.A., Hamstra, S.J., 1999. Gap detection thresholds as a function of tonal duration for younger and older listeners. J. Acoust. Soc. Am. 106, 371–380.
Schneider, B.A., Daneman, M., Pichora-Fuller, M.K., 2002. Listening in aging adults: from discourse comprehension to psychoacoustics. Can. J. Exp. Psychol. 56, 139–152.
Schuknecht, H.F., Woellner, R.C., 1955. An experimental and clinical study of deafness from lesions of the cochlear nerve. J. Laryngol. Otol. 69, 75–97.
Shahin, A.J., Picton, T.W., Miller, L.M., 2009. Brain oscillations during semantic evaluation of speech. Brain Cogn. 70, 259–266.
Shahin, A.J., Trainor, L.J., Roberts, L.E., Backer, K.C., Miller, L.M., 2010. Development of auditory phase-locked activity for music sounds. J. Neurophysiol. 103, 218–229.
Skoe, E., Krizman, J., Kraus, N., 2013a. The impoverished brain: disparities in maternal education affect the neural response to sound. J. Neurosci. 33, 17221–17231.
Skoe, E., Krizman, J., Anderson, S., Kraus, N., 2013b. Stability and plasticity of auditory brainstem function across the lifespan. Cereb. Cortex. http://dx.doi.org/10.1093/cercor/bht311.
Snyder, J.S., Alain, C., 2005. Age-related changes in neural activity associated with concurrent vowel segregation. Brain Res. Cogn. Brain Res. 24, 492–499.
Song, J.H., Nicol, T., Kraus, N., 2011. Test-retest reliability of the speech-evoked auditory brainstem response. Clin. Neurophysiol. 122, 346–355.
Strait, D.L., O'Connell, S., Parbery-Clark, A., Kraus, N., 2013. Musicians' enhanced neural differentiation of speech sounds arises early in life: developmental evidence from ages 3 to 30. Cereb. Cortex.
Strouse, A., Ashmead, D.H., Ohde, R.N., Grantham, D.W., 1998. Temporal processing in the aging auditory system. J. Acoust. Soc. Am. 104, 2385–2399.
Suga, N., Gao, E., Zhang, Y., Ma, X., Olsen, J.F., 2000. The corticofugal system for hearing: recent progress. Proc. Natl. Acad. Sci. U.S.A 97, 11807–11814.
Suzuki, Y., Critchley, H.D., Suckling, J., Fukuda, R., Williams, S.C., Andrew, C., Howard, R., Ouldred, E., Bryant, C., Swift, C.G., Jackson, S.H., 2001. Functional magnetic resonance imaging of odor identification: the effect of aging. J. Gerontol. A Biol. Sci. Med. Sci. 56, M756–M760.
Terhardt, E., Stoll, G., Seewann, M., 1982. Algorithm for the extraction of pitch and pitch salience from complex tonal signals. J. Acoust. Soc. Am. 71, 679–687.
Trainor, L.J., Shahin, A.J., Roberts, L.E., 2009. Understanding the benefits of musical training: effects on oscillatory brain activity. Ann. N.Y. Acad. Sci. 1169, 133–142.
Tremblay, K., Souza, P., Piskosz, M., 2002. Aging alters the neural representation of of speech-cues. Neuroreport 13, 1865–1870.
Tremblay, K., Piskosz, M., Souza, P., 2003. Effects of age and age-related hearing loss on the neural representation of speech cues. Clin. Neurophysiol. 114, 1332–1343.
Tzounopoulos, T., Kraus, N., 2009. Learning to encode timing: mechanisms of plasticity in the auditory brainstem. Neuron 62, 463–469.
van Rooij, J., Plomp, R., 1992. Auditive and cognitive factors in speech perception by elderly listeners. III. Additional data and final discussion. J. Acoust. Soc. Am. 91, 1028–1033.
Vander Werff, K.R., Burns, K.S., 2010. Brainstem responses to speech in younger and older adults. Ear Hear. 32, 168–180.
Vander Werff, K.R., Burns, K.S., 2011. Brain stem responses to speech in younger and older adults. Ear Hear. 32, 168–180.
Welford, A.T., 1981. Signal, noise, performance, and age. Hum. Factors 23, 97–109.
Wong, P.C., Ettlinger, M., Sheppard, J.P., Gunasekera, G.M., Dhar, S., 2010. Neuroanatomical characteristics and speech perception in noise in older adults. Ear Hear. 31, 471–479.
Woods, D.L., Clayworth, C.C., 1986. Age-related changes in human middle latency auditory evoked potentials. Electroencephalogr. Clin. Neurophysiol. 65, 297–303.
Woods, D.L., Alain, C., Covarrubias, D., Zaidel, O., 1993. Frequency-related differences in the speed of human auditory processing. Hear. Res. 66, 46–52.
Xiong, Y., Zhang, Y., Yan, J., 2009. The neurobiology of sound-specific auditory plasticity: a core neural circuit. Neurosci. Biobehav. Rev. 33, 1178–1184.
Yan, J., Zhang, Y., Ehret, G., 2005. Corticofugal shaping of frequency tuning curves in the central nucleus of the inferior colliculus of mice. J. Neurophysiol. 93, 71–83.
Zendel, B.R., Alain, C., 2014. Enhanced attention-dependent activity in the auditory cortex of older musicians. Neurobiol. Aging 35, 55–63.
Zhou, D., Lebel, C., Evans, A., Beaulieu, C., 2013. Cortical thickness asymmetry from childhood to older adulthood. Neuroimage 83, 66–74.