

Afferent-efferent connectivity between auditory brainstem and cortex accounts for poorer speech-in-noise comprehension in older adults

Running title: Aging and brainstem-cortical connectivity

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45 **ABSTRACT**

46 Age-related hearing loss leads to poorer speech comprehension, particularly in noise. Speech-in-noise
47 (SIN) deficits among the elderly could result from weaker neural activity within, or poorer signal
48 transmission between brainstem and auditory cortices. By recording neuroelectric responses from
49 brainstem (BS) and primary auditory cortex (PAC), we show that beyond simply attenuating neural
50 activity, hearing loss in older adults compromises the transmission of speech information between
51 subcortical and cortical hubs of the auditory system. The strength of afferent BS→PAC neural signaling
52 (but not the reverse efferent flow; PAC→BS) varied with mild declines in hearing acuity and this
53 “bottom-up” functional connectivity robustly predicted older adults’ SIN perception. Our neuroimaging
54 findings underscore the importance of brain connectivity, particularly afferent neural communication, in
55 understanding the biological basis of age-related hearing deficits in real-world listening environments.

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60 **Keywords:** Aging; auditory evoked potentials; auditory cortex; frequency-following response (FFR);
61 functional connectivity; source waveform analysis; neural speech processing

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64 INTRODUCTION

65 Difficulty perceiving speech in noise (SIN) is a hallmark of aging. Hearing loss and reduced
66 cognitive flexibility may contribute to speech comprehension deficits that emerge after the fourth decade
67 of life (Humes, 1996; Humes et al., 2012). Yet, older adults' SIN difficulties persist even without
68 substantial hearing impairments (Gordon-Salant and Fitzgibbons, 1993; Schneider et al., 2002),
69 suggesting robust speech processing requires more than audibility.

70 Emerging views of aging suggest that in addition to peripheral changes (i.e., cochlear pathology)
71 (e.g., Chambers et al., 2016), older adults' perceptual SIN deficits might arise due to poorer sensory
72 encoding, *transmission*, and decoding of acoustic speech features within the brain's central auditory
73 pathways (Schneider et al., 2002; Wong et al., 2010; Peelle et al., 2011; Anderson, White-Schwoch, et al.,
74 2013a). Although "central presbycusis" offers a powerful framework for studying the perceptual
75 consequences of aging (Humes, 1996), few studies have explicitly investigated how the auditory system
76 extracts and transmits features of the speech signal across different levels of the auditory neuroaxis.
77 Senescent changes have been observed in pontine, midbrain, and cortical neurons (Peelle and Wingfield,
78 2016). Yet, such insight into brainstem-cortex interplay has been limited to animal models (Chambers et
79 al., 2016).

80 Age-related changes in hierarchical auditory processing can be observed in scalp-recorded
81 frequency-following responses (FFR) and event-related brain potentials (ERPs), dominantly reflecting
82 activity of midbrain and cerebral structures, respectively (Bidelman et al., 2013). Both speech-FFRs
83 (Anderson, White-Schwoch, et al., 2013b; Bidelman, Villafuerte, et al., 2014) and ERPs (Tremblay et al.,
84 2003; Alain et al., 2014; Bidelman, Villafuerte, et al., 2014) reveal age-related changes in the
85 responsiveness (amplitude) and precision (timing) of how subcortical and cortical stages of the auditory
86 system extract complex sounds. In our studies recording these potentials simultaneously, we showed
87 aging is associated with increased redundancy (higher shared information) between brainstem and cortical
88 representations for speech (Bidelman, Villafuerte, et al., 2014; Bidelman et al., 2017). Our previous
89 findings imply that SIN problems in older listeners might result from aberrant *transmission* of speech
90 signals from brainstem en route to auditory cortex, a possibility that has never been formally tested.

91 A potential candidate for these central encoding/transmission deficits in aging (Humes, 1996)
92 could be the well-known afferent and efferent (corticofugal) projections that carry neural signals
93 bidirectionally between brainstem and primary auditory cortex (BS↔PAC) (Suga et al., 2000; Bajo et al.,
94 2010). Descending corticocollicular (PAC→BS) fibers have been shown to calibrate sound processing of
95 midbrain neurons by fine tuning their receptive fields in response to behaviorally relevant stimuli (Suga et
96 al., 2000). Germane to our studies, corticofugal efferents drive learning-induced plasticity in animals
97 (Bajo et al., 2010) and may also account for the neuroplastic enhancements observed in human FFRs

98 across the age spectrum (Musacchia et al., 2007; Wong et al., 2007; Anderson, White-Schwoch, et al.,
99 2013b). While assays of olivocochlear (peripheral efferent) function are well-established (e.g.,
100 otoacoustic emissions; de Boer and Thornton, 2008) there have been no direct measurements of
101 corticofugal (central efferent) system function in humans, despite its assumed role in complex listening
102 skills like SIN (Slee and David, 2015).

103 To elucidate brainstem-cortical reciprocity in humans, we recorded neuroelectric FFR and ERP
104 responses during active speech perception. Examining older adults with normal or mild hearing loss for
105 their age allowed us to investigate how hierarchical coding is changed with declining sensory input. We
106 used source imaging and functional connectivity analyses to parse activity *within* and directed (causal)
107 transmission *between* sub- and neo-cortical levels. To our knowledge, this is the first study to document
108 afferent and corticofugal efferent function in human speech processing. We hypothesized (i) hearing loss
109 would alter the relative strengths of afferent (BS→PAC) and/or corticofugal (PAC→BS) signaling and
110 more importantly, (ii) poorer connectivity would account for older adults' perceptual SIN deficits.
111 Beyond aging, such findings would also establish a biological mechanism to account for the pervasive,
112 parallel changes in brainstem and cortical speech-evoked responses previously observed in highly skilled
113 listeners (e.g., musicians) and certain neuropathologies (Musacchia et al., 2008; Bidelman and Alain,
114 2015; Bidelman et al., 2017).

115 **METHODS**

116 **Participants**

117 Thirty-two older adults aged 52-75 years were recruited from the Greater Toronto Area to
118 participate in our ongoing studies on aging and the auditory system. None reported history of neurological
119 or psychiatric illness. Pure-tone audiometry was conducted at octave frequencies between 250 and 8000
120 Hz. Based on listeners' hearing thresholds, the cohort was divided into normal and hearing-impaired
121 groups (Fig. 1A). In this study, normal-hearing (NH; $n=13$) listeners were classified as having average
122 thresholds (250 to 8000 Hz) better than 25 dB HL across both ears, whereas listeners with hearing loss
123 (HL; $n=19$) had average thresholds poorer than 25 dB HL. This division resulted in pure-tone averages
124 (PTAs) (i.e., mean of 500, 1000, 2000 Hz) that were ~10 dB better in NH compared to HL listeners ($mean$
125 $\pm SD$; NH: 15.3 ± 3.27 dB HL, HL: 26.4 ± 7.1 dB HL; $t_{2,71} = -5.95$, $p < 0.0001$). This definition of hearing
126 impairment further helped the post hoc matching of NH and HL listeners on other demographic variables
127 while maintaining adequate sample sizes per group. Both groups had signs of age-related presbycusis at
128 very high frequencies (8000 Hz), which is typical in older adults. However, it should be noted that the
129 audiometric thresholds of our NH listeners were better than the hearing typically expected based on the
130 age range of our cohort, even at higher frequencies (Pearson et al., 1995; Cruickshanks et al., 1998).

131 Importantly, besides hearing, the groups were otherwise matched in age (NH: 66.2 ± 6.1 years, HL:
132 70.4 ± 4.9 years; $t_{2,22} = -2.05$, $p = 0.052$) and gender balance (NH: 5/8 male/female; HL: 11/8; Fisher's exact
133 test, $p = 0.47$). Age and hearing loss were not correlated in our sample (Pearson's $r = 0.29$, $p = 0.10$).
134 Participants were compensated for their time and gave written informed consent in compliance with a
135 protocol approved by the Baycrest Centre research ethics committee.

136 **Stimuli and task**

137 Three tokens from the standardized UCLA version of the Nonsense Syllable Test were used in
138 this study (Dubno and Schaefer, 1992). These tokens were naturally produced English consonant-vowel
139 phonemes (/ba/, /pa/, and /ta/), spoken by a female talker. Each phoneme was 100-ms in duration and
140 matched in terms of average root mean square sound pressure level (SPL). Each had a common voice
141 fundamental frequency ($F_0 = 150$ Hz) and first and second formants ($F_1 = 885$, $F_2 = 1389$ Hz). This
142 relatively high F_0 ensured that FFRs would be of dominantly subcortical origin and cleanly separable
143 from cortical activity (Bidelman, 2018), since PAC phase-locking (cf. "cortical FFRs"; Coffey et al.,
144 2016) is rare above ~ 100 Hz (Brugge et al., 2009; Bidelman, 2018). CVs were presented in both clear
145 (i.e., no noise) and noise-degraded conditions. For each noise condition, the stimulus set included a total
146 of 3000 /ba/, 3000 /pa/, and 210 /ta/ tokens (spread evenly over three blocks to allow for breaks).

147 For each block, speech tokens were presented back-to-back in random order with a jittered
148 interstimulus interval (95-155 ms, 5ms steps, uniform distribution). Frequent (/ba/, /pa/) and infrequent
149 (/ta/) tokens were presented according to a pseudo-random schedule such that at least two frequent stimuli
150 intervened between target /ta/ tokens. Listeners were asked to respond each time they detected the target
151 (/ta/) via a button press on the computer. Reaction time (RT) and detection accuracy (%) were logged.
152 These procedures were then repeated using an identical speech triplet mixed with eight talker noise
153 babble (cf. Killion et al., 2004) at a signal-to-noise ratio (SNR) of 10 dB. Thus, in total, there were 6
154 blocks (3 clear, 3 noise). The babble was presented continuously so that it was not time-locked to the
155 stimulus, providing a constant backdrop of interference in the noise condition (e.g., Alain et al., 2012;
156 Bidelman, 2016; Bidelman and Howell, 2016). Comparing behavioral performance between clear and
157 degraded stimulus conditions allowed us to assess the impact of acoustic noise and differences between
158 normal and hearing-impaired listeners in speech perception. Importantly, our task ensured that
159 FFRs/ERPs were recorded online, during *active* speech perception. This helps circumvent issues in
160 interpreting waveforms recorded across different attentional states or task demands (for discussion, see
161 Bidelman, 2015a).

162 Stimulus presentation was controlled by a MATLAB (The Mathworks, Inc.; Natick, MA) routed
163 to a TDT RP2 interface (Tucker-Davis Technologies; Alachua, FL) and delivered binaurally through
164 insert earphones (ER-3; Etymotic Research; Elk Grove Village, IL). The speech stimuli were presented at

165 an intensity of 75 dB_A SPL (noise at 65 dB_A SPL) using alternating polarity and FFRs/ERPs were derived
166 by summing an equal number of condensation and rarefaction responses. This approach helps minimize
167 stimulus artifact and cochlear microphonic from scalp recordings (which flip with polarity) and
168 accentuates portions of the FFR related to signal envelope, i.e., fundamental frequency (F0) (Aiken and
169 Picton, 2008; Skoe and Kraus, 2010b; Smalt et al., 2012).

170 **QuickSIN test**

171 We measured listeners' speech reception thresholds in noise using the QuickSIN test (Killion et
172 al., 2004). Participants were presented lists of six sentences with five key words per sentence embedded
173 in four-talker babble noise. Sentences were presented at 70 dB SPL using pre-recorded SNRs that
174 decreased in 5 dB steps from 25 dB (very easy) to 0 dB (very difficult). Listeners scored one point for
175 each key word correctly repeated. "SNR loss" (in dB) was determined as the SNR required to correctly
176 identify 50% of the key words (Killion et al., 2004). SNR loss reflects the performance in noise compared
177 to normal-hearing persons' performance in noise. Consequently, larger scores reflect worse performance
178 in SIN recognition. We averaged SNR loss from four list presentations per listener.

179 **Electrophysiological recordings and analysis**

180 *EEG acquisition and preprocessing.* During the primary behavioral task, neuroelectric activity
181 was recorded from 32 channels at standard 10-20 electrode locations on the scalp (Oostenveld and
182 Praamstra, 2001). Recording EEGs during the active listening task allowed us to control for attention and
183 assess the relative influence of brainstem and cortex during online speech perception. The montage
184 included electrode coverage over frontocentral (Fz, Fp1/2, F3/4, F7/8, F9/10, C3/4), temporal (T7/8,
185 TP7/9, TP8/10), parietal (Pz, P3/4, P7/8), and occipital-cerebellar (Oz, O1/2, CB1/2, Iz) sites. Electrodes
186 placed along the zygomatic arch (FT9/10) and the outer canthi and superior/inferior orbit of the eye
187 (IO1/2, LO1/2) monitored ocular activity and blink artifacts. Electrode impedances were maintained at \leq
188 5 k Ω . EEGs were digitized at a sampling rate of 20 kHz using SynAmps RT amplifiers (Compumedics
189 Neuroscan; Charlotte, NC). Data were re-referenced off-line to a common average reference for further
190 analyses.

191 Subsequent pre-processing was performed in BESA® Research v6.1 (BESA, GmbH). Ocular
192 artifacts (saccades and blinks) were first corrected in the continuous EEG using a principal component
193 analysis (PCA) (Picton et al., 2000). Cleaned EEGs were then epoched (-10-200 ms), baseline corrected
194 to the pre-stimulus period, and subsequently averaged in the time domain to obtain compound evoked
195 responses, containing both brainstem and cortical activity (Bidelman et al., 2013), for each stimulus
196 condition per participant.

197 *Source waveform derivations.* Scalp potentials (sensor-level recordings) were transformed to
198 source space using BESA. We seeded three dipoles located in (i) midbrain of the brainstem (BS) and (ii-
199 iii) bilateral primary auditory cortex (PAC) (Bidelman, 2018). Dipole orientations for the PAC sources
200 were set using the tangential component of BESA's default auditory evoked potential (AEP) montage
201 (Scherg et al., 2002). The tangential component was selected given that it dominantly explains the auditory
202 cortical ERPs (Picton et al., 1999). Orientation of the BS source followed the oblique, fronto-centrally
203 directed dipole of the FFR (Bidelman, 2015b). Focusing on BS and PAC source waveforms allowed us to
204 reduce the dimensionality of the scalp data from 32 sensors to 3 source channels and allowed specific
205 hypothesis testing regarding hearing-induced changes in brainstem-cortical connectivity. While simplistic,
206 this model's average goodness of fit (GoF) across groups and stimuli was $88.1 \pm 3.8\%$, meaning that
207 residual variance (RV) between recorded and source-modeled data was low ($RV = 11.9 \pm 3.9\%$).

208 To extract individuals' source waveforms within each region of interest (ROI), we transformed
209 their scalp recordings into source-level responses using a virtual source montage (Scherg et al., 2002). This
210 digital re-montaging applies a spatial filter to all electrodes (defined by the foci of our three-dipole
211 configuration). Relative weights were optimized in BESA to image activity within each brain ROI while
212 suppressing overlapping activity stemming from other active brain regions (for details, see Scherg and
213 Ebersole, 1994; Scherg et al., 2002). For each participant, the model was held fixed and was used as a
214 spatial filter to derive their source waveforms (Alain et al., 2009; Zendel and Alain, 2014), reflecting the
215 neuronal current (in units nAm) as seen *within* each anatomical ROI. Compound source waveforms were
216 then bandpass filtered into high (100–1000 Hz) and low (1–30 Hz) frequency bands to isolate the periodic
217 brainstem FFR vs. slower cortical ERP waves from each listeners' compound evoked response (Musacchia
218 et al., 2008; Bidelman et al., 2013; Bidelman, 2015a). Comparing FFR and ERP source waveforms
219 allowed us to assess the relative contributions of brainstem and cortical activity to SIN comprehension in
220 normal and hearing-impaired listeners. Results reported herein were collapsed across /ba/ and /pa/ tokens
221 to reduce the dimensionality of the data. Infrequent /ta/ responses were not analyzed given the limited
222 number of trials for this condition and to avoid mismatch negativities in our analyses.

223 *FFR source waveforms.* We measured the magnitude of the source FFR F0 to quantify the degree of
224 neural phase-locking to the speech envelope rate, a neural correlate of “voice pitch” encoding (Bidelman
225 and Krishnan, 2010; Parbery-Clark et al., 2013; Bidelman and Alain, 2015). F0 was the most prominent
226 spectral component in FFR spectra (see Fig. 4) and is highly replicable both within and between listeners
227 (Bidelman et al., 2018). F0 was taken as the peak amplitude in response spectra nearest the 150 Hz bin, the
228 expected F0 based on our speech stimuli.

229 *ERP source waveforms.* Prominent components of the ERP source responses were quantified in
230 latency and amplitude using BESA's automated peak analysis for both left and right PAC waveforms in

231 each participant. Appropriate latency windows were first determined by manual inspection of grand
232 averaged traces. For each participant, the P1 wave was then defined as the point of maximum upward
233 deflection from baseline between 40 and 70 ms; N1 as the negative-going deflection within 90 and 145 ms;
234 P2 as the maximum positive deflection between 145 and 175 ms (Hall, 1992). These measures allowed us to
235 evaluate the effects of noise and hearing loss on the magnitude and efficiency of cortical speech processing.
236 Additionally, differentiation between hemispheres enabled us to investigate the relative contributions of
237 each auditory cortex to SIN processing.

238 **Functional connectivity**

239 We measured causal (directed) information flow between nodes of the brainstem-cortical network
240 using phase transfer entropy (PTE) (Lobier et al., 2014). For data reduction purposes, responses were
241 collapsed across left and right hemispheres and stimuli prior to connectivity analysis. PTE is a non-
242 parametric, information theoretic measure of directed signal interaction. It is ideal for measuring
243 functional connectivity between regions because it can detect nonlinear associations between signals and
244 is robust against the volume conducted cross-talk in EEG (Vicente et al., 2011; Hillebrand et al., 2016).
245 PTE was estimated using the time series of the instantaneous phases of pairwise signals (i.e., BS and PAC
246 waveforms) (Lobier et al., 2014; Hillebrand et al., 2016). PTE was computed according to Eq. 1:

$$247 \quad PTE_{X \rightarrow Y} = \sum p(y_{t+\tau}, y_t^m, x_t^n) \log_2 \left[\frac{p(y_{t+\tau} | y_t^m, x_t^n)}{p(y_{t+\tau}, y_t^n)} \right] \quad (\text{Eq. 1})$$

248 where X and Y are the ROI signals and the $\log(\cdot)$ term is the conditional probabilities between
249 signals at time $t+\tau$ for sample m and n . The probabilities were obtained by building histograms of
250 occurrences of pairs of phase estimates in the epoch (Lobier et al., 2014). Following Hillebrand et al.
251 (2016), the number of histogram bins was set to $e^{0.626+0.4\ln(Ns-\tau-1)}$ (Otnes and Enochson, 1972). The
252 prediction delay τ was set at 100 ms, to include coverage of the entirety of the FFR signal and early
253 cortical ERPs (see Fig. 2). Although this τ was based on *a priori* knowledge of the ERP time course, it
254 should be noted that PTE yields similar results with comparable sensitivity across a wide range of
255 analysis lags (Lobier et al., 2014).

256 Intuitively, PTE is understood as the reduction in information (units bits) necessary to describe
257 the present ROI_Y signal using both the past of ROI_X and ROI_Y . PTE cannot be negative and has no upper
258 bound. Higher values indicate stronger connectivity, whereas $PTE_{X \rightarrow Y} = 0$ implies no directed signaling. In
259 this sense, it is similar to the definition of Granger Causality (Barnett et al., 2009), which states that ROI_X
260 has a causal influence on the target ROI_Y if knowing the past of both signals improves the prediction of
261 the target's future compared to knowing only its past. Yet, PTE has several important advantages over
262 other connectivity metrics (Lobier et al., 2014): (i) PTE is more robust to realistic amounts of noise and

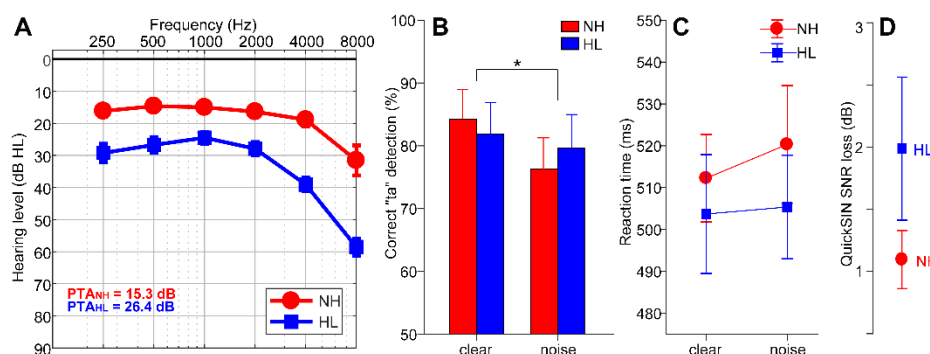
263 linear mixing in the EEG that can produce false-positive connections; (ii) PTE relaxes assumptions about
264 data normality and is therefore model-free; (iii) PTE is asymmetric so it can be computed bi-directionally
265 between pairs of sources ($X \rightarrow Y$ vs. $Y \rightarrow X$) to infer causal, directional flow of information between
266 interacting brain regions. Computing PTE in both directions between BS and PAC allowed us to quantify
267 the relative weighting of information flowing between subcortical and cortical ROIs in both feedforward
268 (afferent; BS \rightarrow PAC) and feedback (efferent; PAC \rightarrow BS) directions.

269 Statistical analysis and Experimental Design

270 Unless otherwise noted, two-way mixed model ANOVAs were conducted on all dependent
271 variables (GLIMMIX, SAS® 9.4, SAS Institute; Cary, NC). Group (2 levels; NH, HL) and stimulus SNR
272 (2 levels; clear, noise) functioned as fixed effects; participants served as a random factor. With the
273 exception of ERP amplitude measures (see below), initial diagnostics confirmed normality and
274 homogeneity of variance assumptions for parametric statistics. Tukey–Kramer adjustments controlled
275 Type I error inflation. An *a priori* significance level was set at $\alpha = 0.05$ for all statistical analyses. Effect
276 sizes are reported as Cohen’s *d* (Wilson, 2018). Independent samples *t*-tests (un-pooled variance, two-
277 tailed) were used to contrast demographic variables.

278 Correlational analyses (Pearson’s *r*) and robust regression (bisquare weighting) were used to
279 evaluate relationships between neural and behavioral measures. Robust fitting was achieved using the
280 ‘fitlm’ function in MATLAB. We used an efficient, bootstrapping implementation of the Sobel statistic
281 (Sobel, 1982; Preacher and Hayes, 2004) ($N=1000$ resamples) to test for mediation effects between
282 demographic, neural connectivity, and behavioral measures.

283



284

285 **Figure 1: Audiometric and perceptual results.** (A) Audiograms for listeners with normal
286 hearing (NH) and hearing loss (HL). Hearing was ~10 dB better in NH vs. HL listeners. (B)
287 Behavioral accuracy for detecting infrequent /ta/ tokens in clear and noise-degraded conditions.
288 Noise-related declines in behavioral performance were prominent but no group differences were
289 observed. (C) Reaction times (RTs) for speech detection were similar between groups and speech
290 SNRs. (D) HL listeners showed more variability and marginally poorer QuickSIN performance
291 than NH listeners. errorbars = \pm s.e.m., * $p < 0.05$.

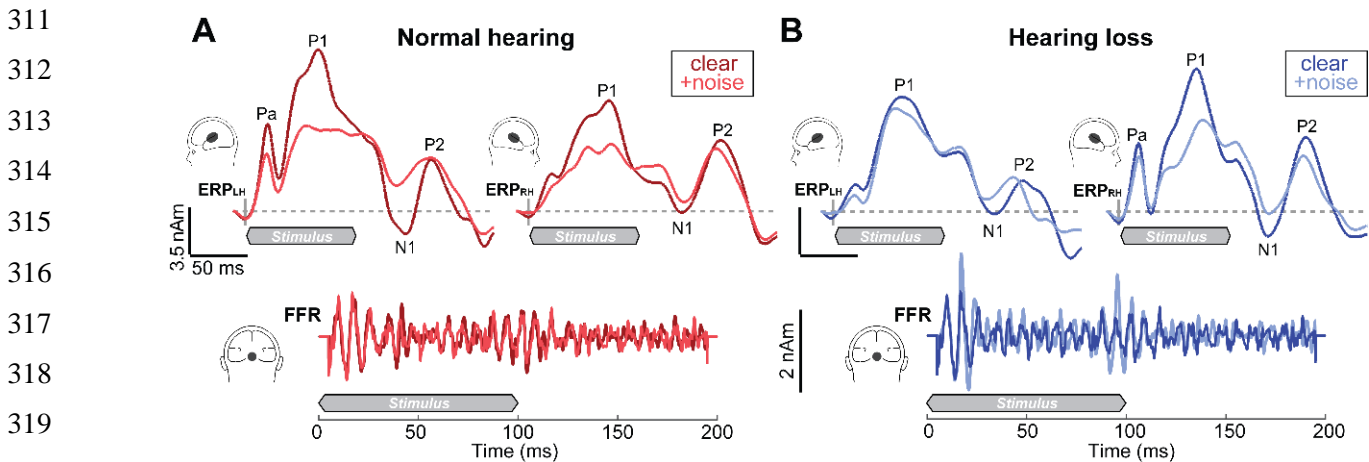
292 RESULTS

293 Behavioral data

294 Behavioral accuracy and reaction time for target speech detection are shown for each group and
295 noise condition in Figure 1. An ANOVA revealed a main effect of SNR on /ta/ detection accuracy, which
296 was lower for noise-degraded compared to clear speech [$F_{1,30}=5.66, p=0.024, d=0.88$; Fig. 1B]. However,
297 groups differed neither in their accuracy [$F_{1,30}=0.01, p=0.94; d=0.04$] nor speed [$F_{1,30}=0.47, p=0.49$;
298 $d=0.26$; Fig. 1C] of speech identification. On average, HL individuals achieved QuickSIN performance
299 within ~1 dB of NH listeners, and scores did not differ between groups [$t_{2,35}=-1.43, p=0.16$] (Fig. 1D).
300 Nevertheless, HL listeners showed more inter-subject variability in SIN performance compared to NH
301 listeners [Equal variance test (two-sample F -test): $F_{18,12}=8.81, p=0.0004$]. Collectively, these results
302 suggest that the hearing loss in our sample was not yet egregious enough to yield substantial deficits in
303 speech perception.

304 Electrophysiological data

305 Speech-evoked brainstem FFR and cortical ERP source waveforms are shown in Figure 2.
306 Cortical activity appeared as a series of obligatory waves developing over ~200 ms after the initiation of
307 speech that were modulated by noise and cerebral hemisphere. Noise-related changes in the ERPs were
308 particularly prominent in the earlier P1 and N1 deflections reflecting the initial registration of sound in
309 medial portions of PAC and secondary auditory cortex (Scherg and von Cramon, 1986; Liégeois-Chauvel
310 et al., 1994; Picton et al., 1999).



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Figure 2: ERP (top traces) and FFR (bottom) source waveforms reflect the simultaneous encoding of speech within cortical and brainstem tiers of the auditory system. (A) NH listeners show a leftward asymmetry in PAC responses compared to HL listeners (B), who show stronger activation in right PAC. Noise weakens the cortical ERPs to speech across the board, particularly in the timeframe of P1 and N1, reflecting the initial registration of sound in PAC. In contrast to cortical responses, BS FFRs are remarkably similar between groups and noise conditions. Shaded regions demarcate the 100 ms speech stimulus. BS, brainstem; PAC, primary auditory cortex.

321 These observations were confirmed via quantitative analysis of source ERP latency and amplitude
 322 (Fig. 3). ANOVA diagnostics indicated positive skew in ERP amplitude measures. Thus, we used a
 323 natural log transform in analyses of the cortical amplitude data. An ANOVA conducted on log-
 324 transformed ERP amplitudes revealed a main effect of SNR for both P1 and N1 with stronger responses
 325 for clear compared to noise-degraded speech [P1 amp: $F_{1,94}=12.67, p<0.001, d=1.28$; N1 amp: $F_{1,94}=6.70, p=0.01, d=0.93$; data not shown]. These results replicate the noise-related degradation in speech-
 326 evoked activity observed in previous studies (e.g., Alain et al., 2014; Bidelman and Howell, 2016).
 327 Unlike the early ERP waves, P2 amplitude varied between hemispheres [$F_{1,94}=9.38, p=0.003, d=1.10$],
 328 with greater activation in right PAC. There was also a main effect of group with larger P2 responses in
 329 NH listeners [$F_{1,30}=4.74, p=0.038, d=0.78$] (Fig. 3A and 3B). The P2 deflection is thought to reflect the
 330 signal's identity, recognition of perceptual objects, and perceptual-phonetic categories of speech (Wood et
 331 al., 1971; Eulitz et al., 1995; Alain et al., 2007; Bidelman et al., 2013; Bidelman and Lee, 2015; Bidelman
 332 and Yellamsetty, 2017). The effects of age and noise on the P2 wave could indicate deficits in mapping
 333 acoustic details into a more abstract phonemic representation.
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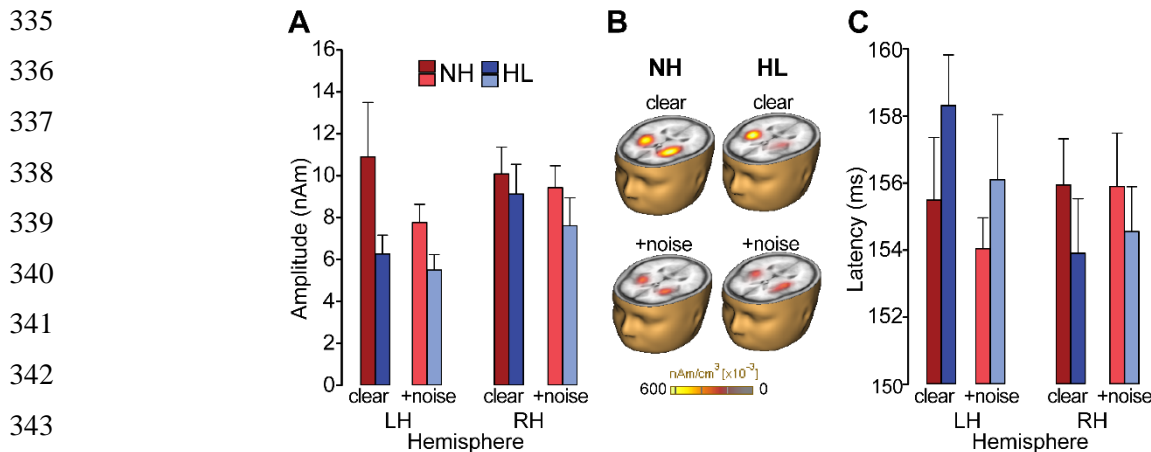


Figure 3: Cortical speech processing is modulated by noise interference, hearing status, and cerebral hemisphere. (A) P2 amplitudes are stronger in NH listeners regardless of SNR. (B) Brain volumes show distributed source activation maps using Cortical Low resolution electromagnetic tomography Analysis Recursively Applied (CLARA; BESA v6.1) (Jordanov et al., 2014). Functional data are overlaid on the BESA brain template (Richards et al., 2016). (C) P2 latency revealed a group x hemispheric interaction. In HL listeners, responses were ~3 ms earlier in right compared to left hemisphere (R<L) whereas no latency differences were observed in NH ears (L=R). errorbars = \pm s.e.m.

344
 345 For latency, no effects were observed at P1. However, hemispheric differences were noted for N1
 346 latencies [$F_{1,94}=9.49, p=0.003, d=1.11$], where responses were ~4 ms earlier in the right compared to left
 347 hemisphere across both groups. P2 latency also showed a group x hemisphere interaction [$F_{1,93}=5.27,$
 348 $p=0.02, d=0.82$] (Fig. 3B). Post hoc analyses revealed a significant asymmetry for the HL group: P2
 349 latencies were ~3 ms earlier in right relative to left PAC whereas no hemispheric asymmetry was

350 observed in the NH listeners. These results indicate an abnormal hemispheric asymmetry beginning as
351 early as N1 extending through P2 (~150 ms) in listeners with mild hearing impairment.

352 In contrast to slow cortical activity, brainstem FFRs showed phase-locked neural activity to the
353 periodicities of speech (Fig. 2, bottom traces). Analysis of response spectra revealed strong energy at the
354 voice fundamental frequency (F0) and weaker energy tagging the upper harmonics of speech (Fig. 4).
355 Previous FFR studies have shown that older adults have limited coding of the high-frequency harmonics
356 of speech (e.g., Anderson, Parbery-Clark, et al., 2013; Bidelman, Villafuerte, et al., 2014; Clinard and
357 Cotter, 2015; Bidelman et al., 2017). The latter is particularly susceptible to noise (Bidelman and
358 Krishnan, 2010; Bidelman, 2016) and hearing loss (Henry and Heinz, 2012) and reduced amplitudes may
359 be attributable to age- and hearing-related changes in brainstem phase-locking (Parthasarathy et al.,
360 2014). Weaker harmonic energy of the F0 may also be due to the relatively short duration of vowel
361 periodicity (< 40 ms) of our stimuli. Group and noise-related effects in FFRs were less apparent than in
362 the ERPs. An ANOVA conducted on FFR F0 amplitudes showed that FFR in older adults was little
363 affected by hearing loss [main effect of group: $F_{1,30}=0.38$, $p=0.54$, $d=0.22$] or background noise [main of
364 effect of SNR: $F_{1,30}=0.41$, $p=0.53$, $d=0.23$] (Fig. 4B). These results suggest that neither the severity of
365 noise nor mild hearing impairment had an appreciable effect on the fidelity of brainstem F0 coding in our
366 listeners. Yet, comparing across levels of the neuroaxis, age-related hearing loss had a differential effect
367 on complex sound coding across levels, exerting a stronger effect at cortical vs. subcortical stages of the
368 auditory system (cf. Bidelman, Villafuerte, et al., 2014).

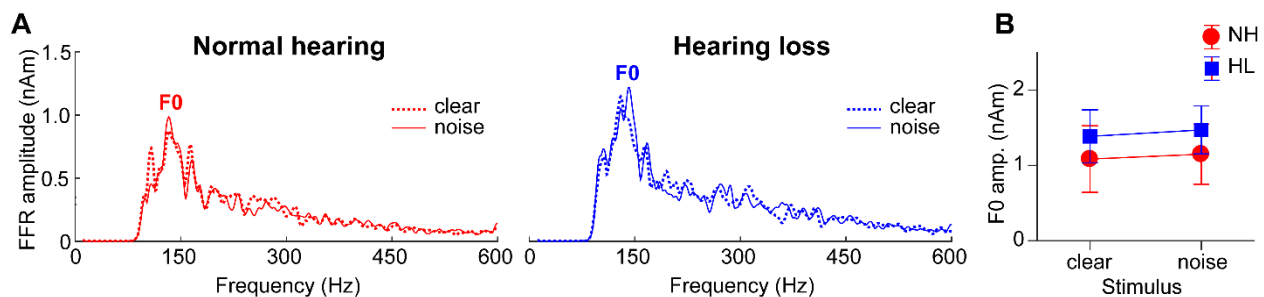


Figure 4: Brainstem speech processing as a function of noise and hearing loss. (A) Source FFR spectra for response to clear and degraded speech. Strong energy is observed at the voice fundamental frequency (F0) but much weaker energy tagging the upper harmonics of speech, consistent with age-related declines in high-frequency spectral coding. Group and noise-related effects in FFRs were less apparent than in the cortical ERPs (cf. Fig. 3). errorbars = \pm s.e.m.

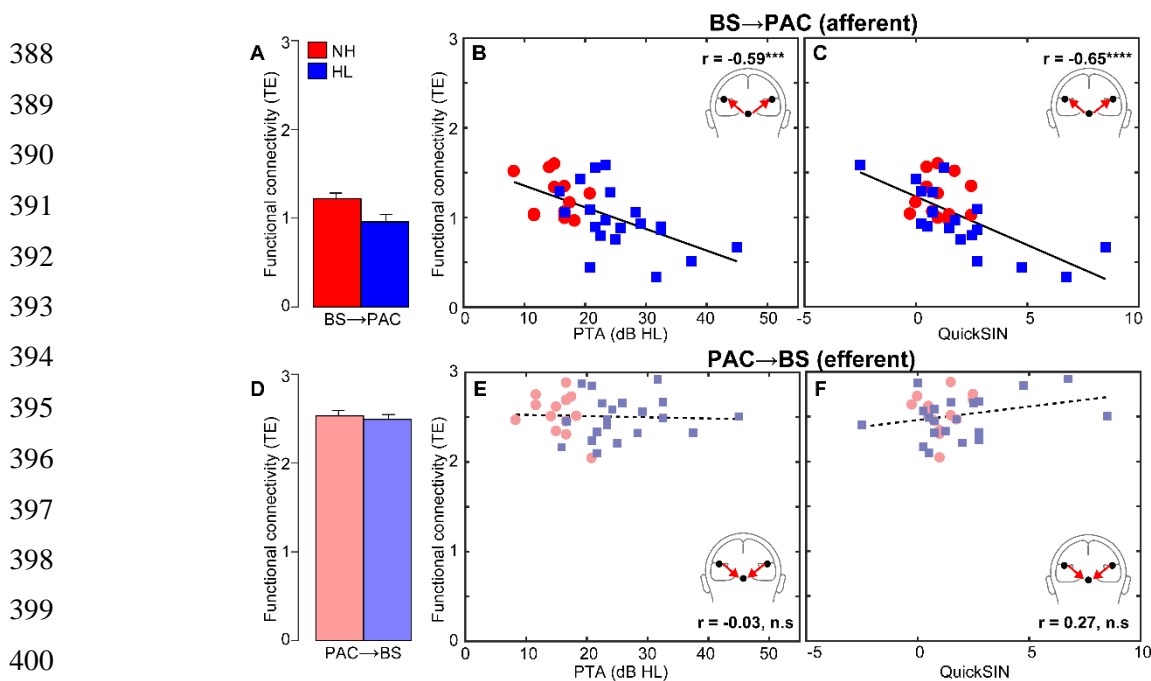
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370 Brainstem-cortical functional connectivity

371 Phase transfer entropy, quantifying the feedforward (afferent) and feedback (efferent) functional
372 connectivity between BS and PAC, is shown in Figure 5. We found that afferent BS→PAC signaling was
373 stronger in NH vs. HL listeners [$F_{1,30}=5.52$, $p=0.0256$, $d=0.84$] (Fig. 5A) and negatively correlated with
374 the degree of listeners' hearing impairment based on their PTAs (Fig. 5B) [$r=-0.59$, $p=0.0004$].

375 Individuals with poorer hearing acuity showed reduced neural signaling directed from BS to PAC. More
376 interestingly, we found afferent connectivity also predicted behavioral QuickSIN scores (Fig. 5C) [$r=-$
377 0.65 , $p<0.0001$], such that listeners with weaker BS→PAC transmission showed poorer SIN
378 comprehension (i.e., higher QuickSIN scores)¹.

379 In contrast to afferent flow, efferent connectivity directed from PAC→BS, did not differentiate
380 groups [$F_{1,30}=0.21$, $p=0.65$, $d=0.16$] (Fig. 5D). Furthermore, while efferent connectivity was generally
381 stronger than afferent connectivity [$t_{31}=2.52$, $p=0.0171$], PAC→BS transmission was not correlated with
382 hearing thresholds (Fig. 5E) [$r=-0.03$, $p=0.86$] nor behavioral QuickSIN scores (Fig. 5F) [$r=0.27$,
383 $p=0.14$]. Collectively, connectivity results suggest that mild hearing loss alters the afferent-efferent
384 balance of neural communication between auditory brainstem and cortical structures. However, in the
385 aging auditory system, bottom-up (BS→PAC) transmission appears more sensitive to peripheral hearing
386 loss (as measured by pure tone thresholds) and is more predictive of perceptual speech outcomes than top-
387 down signaling (PAC→BS).



¹ An identical pattern of results was observed when considering correlations between listeners' average audiometric thresholds (from 250-8000 Hz) which defined the NH and HL group membership (see Methods). BS→PAC afferent (but not efferent) connectivity was negatively correlated with average hearing thresholds ($r=-0.63$, $p=0.0001$; data not shown).

Figure 5: Functional connectivity between auditory brainstem and cortex varies with hearing loss and predicts SIN comprehension. (A) Transfer entropy reflecting directed (casual) *afferent* neural signaling from BS→PAC. Afferent connectivity is stronger in normal compared to hearing-impaired listeners. (B) Afferent connectivity is weaker in listeners with poorer hearing (i.e., worse PTA thresholds) and predicts behavioral SIN performance (C). Individuals with stronger BS→PAC connectivity show better (i.e., lower) scores on the QuickSIN. (D) *Efferent* neural signaling from PAC→BS does not vary between NH and HL listeners, suggesting similar top-down processing between groups. Similarly, efferent connectivity did not covary with hearing loss (E) nor did it predict SIN comprehension (F). Solid lines=significant correlations; dotted lines=*n.s.* relationships. errorbars = \pm s.e.m., *** $p < 0.001$, **** $p < 0.0001$.

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402 BS→PAC connectivity was correlated with both mild hearing loss and behavioral QuickSIN
403 measures, which suggests that neural signaling could mediate SIN comprehension in older adults in
404 addition to peripheral hearing loss. To test this possibility, we used Sobel mediation analysis (Sobel,
405 1982; Preacher and Hayes, 2004) to tease apart the contributions of hearing loss (PTA) and afferent
406 connectivity (PTE) on listeners' QuickSIN scores (among the entire sample). The Sobel test contrasts the
407 strength of regression between a pairwise vs. a triplet (mediation) model (i.e., $X \rightarrow Y$ vs. $X \rightarrow M \rightarrow Y$). M is
408 said to completely mediate the relation between the $X \rightarrow Y$ if (i) X first predicts Y on its own, (ii) X
409 predicts M , and (iii) the functional relation between $X \rightarrow Y$ is rendered insignificant after controlling for the
410 mediator M (Baron and Kenny, 1986; Preacher and Hayes, 2004).

411 PTA by itself was a strong predictor of QuickSIN scores (Fig. 6A) [$b=0.13$; $t=3.23$, $p=0.0030$];
412 reduced hearing acuity was associated with poorer SIN comprehension. However, when introducing
413 BS→PAC afferent connectivity into the model, the direct relation between PTA and QuickSIN was no
414 longer significant (Fig. 6B) [Sobel mediation effect: $z=2.42$, $p=0.016$]. PTA predicted the strength of
415 afferent connectivity [$b=-0.02$; $t=-4.01$, $p=0.0004$] and in turn, connectivity predicted QuickSIN scores
416 [$b=-3.28$; $t=-3.12$, $p=0.0041$], but the effect of hearing loss on SIN comprehension was indirectly mediated
417 by BS→PAC connectivity strength². In contrast to afferent signaling, efferent connectivity was not a
418 mediator of SIN comprehension [Sobel $z=-0.16$, $p=0.87$]. However, this result might be anticipated given
419 the lack of group differences in efferent PAC→BS connectivity. These results indicate that while hearing
420 status is correlated with perception, the underlying afferent flow of neural activity from BS→PAC fully
421 mediates older adults' SIN listening skills.

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² Although the causality would be questionable, we also could treat PTA as a mediator between afferent connectivity and QuickSIN scores (i.e., PTA→BS/PAC→QuickSIN). Importantly, this arrangement was not significant [Sobel $z=-13.04$, $p=0.29$]. This (i) indicates hearing loss (PTA) does not mediate the relation between afferent BS→PAC connectivity and SIN and (ii) strengthens the causality of the relation between neural afferent signaling and QuickSIN performance reported in the text.

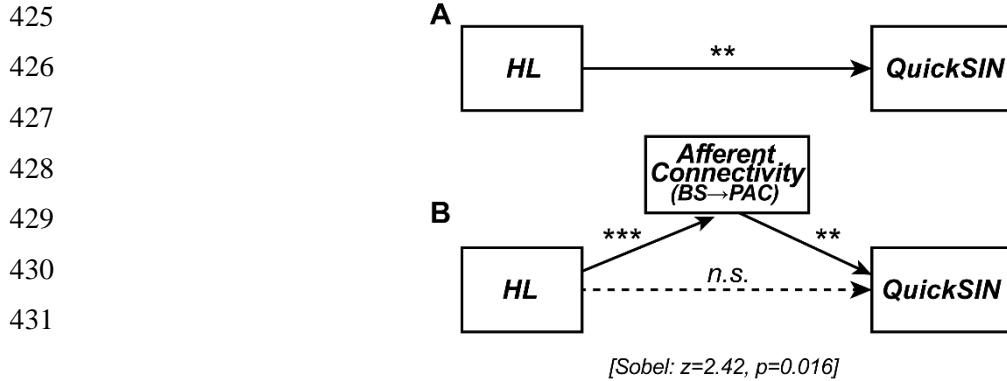


Figure 6: Afferent neural signaling from BS to PAC fully mediates the relation between hearing loss and SIN comprehension. Sobel mediation analysis (Sobel, 1982) between listeners' hearing loss (PTA thresholds), neural connectivity (BS→PAC signaling), and SIN comprehension (QuickSIN scores). Edges show significant relations between pairwise variables identified via linear regression. (A) Hearing loss by itself strongly predicts QuickSIN scores such that reduced hearing is associated with poorer SIN comprehension. (B) Accounting for BS→PAC afferent connectivity renders this relation insignificant (Sobel test: $z=2.42$, $p=0.016$; Sobel, 1982), indicating the strength of neural communication between BS and PAC,

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434 DISCUSSION

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444 Hearing loss differentially alters subcortical vs. cortical auditory processing

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Comparisons between source-level FFRs and ERPs revealed that age-related hearing loss had a differential impact on brainstem vs. cortical speech processing. This finding is reminiscent of animal work demonstrating that online changes in inferior colliculus receptive fields are smaller and in the opposite direction of changes in auditory cortex for the same task (Slee and David, 2015). In our own EEG studies, we showed that hearing loss weakens brainstem encoding of speech (e.g., F0 pitch and formant cues) whereas both age and hearing loss exert negative effects at the cortical level (Bidelman, Villafuerte, et al., 2014). Here, we show that age-related hearing loss reduces amplitude and prolongs the

452 latency of cortical speech activation, indicative of weaker and less efficient neural processing. In contrast,
453 FFRs showed negligible group differences. The lack of significant difference related to age-related
454 hearing loss in lower-level (BS) compared to higher-level (PAC) auditory sources suggests that declines
455 in hearing acuity during the aging process exert a differential effect on neural encoding across functional
456 stages of the auditory hierarchy. Our findings contrast those of prior FFR studies on aging (e.g.,
457 Anderson, Parbery-Clark, et al., 2013; Bidelman, Villafuerte, et al., 2014; Clinard and Cotter, 2015;
458 Bidelman et al., 2017). The discrepancy may be due to the fact that our FFR analyses focused on source
459 responses—a more “pure” measurement of midbrain activity—rather than scalp potentials (previous
460 studies), which can blur the contributions of various subcortical and cortical FFR generators (Coffey et
461 al., 2016; Bidelman, 2018). Moreover, we have found that changes in speech-FFRs only become apparent
462 when hearing impairments exceed PTAs of 30-40 dB HL (Bidelman, Villafuerte, et al., 2014), which are
463 greater than those observed in the present study. All the same, our results bolster the notion that
464 brainstem and cortical mechanisms provide functionally distinct contributions to speech coding
465 (Bidelman et al., 2013) and are differentially susceptible to the various insults of the aging process
466 (Bidelman, Villafuerte, et al., 2014; Bidelman et al., 2017).

467 The lines between peripheral vs. central function and impaired sensory encoding vs. signal
468 transmission issues are difficult to disentangle in humans (Humes, 1996; Marmel et al., 2013; Bidelman,
469 Villafuerte, et al., 2014). Functional changes may result from an imbalance of excitation and inhibition in
470 brainstem (Parthasarathy and Bartlett, 2012), cortex (Chao and Knight, 1997; Caspary et al., 2008), or
471 both structural levels (Bidelman, Villafuerte, et al., 2014). Conversely, neurodegeneration at peripheral
472 sites may partially explain our findings (Makary et al., 2011). Under this interpretation, observed changes
473 in midbrain FFR and cortical PAC activity might reflect maladaptive plasticity in response to deficits
474 earlier (lower) in the pathway. However, we would expect that degeneration due to age alone would
475 produce similar effects between groups since both cohorts were elderly listeners. Instead, it is likely that
476 listeners’ hearing loss (whether central or peripheral in origin) is what produces the cascade of functional
477 changes that alter the neural encoding of speech at multiple stages of the auditory system. In this sense,
478 our data corroborate *in vivo* evidence in animals that central (cortical) gain helps restore diminished
479 sensory input (cf. brainstem) following cochlear damage (Chambers et al., 2016). Interestingly, such
480 peripheral-induced neural rebound is stronger at cortical compared to brainstem levels (Chambers et al.,
481 2016), consistent with the more extensive changes we find in human PAC relative to BS responses. Our
482 data are also consistent with the notion that complex sound representations at peripheral sites (i.e.,
483 brainstem) are more affected by noise than their corresponding cortical representations (Rabinowitz et al.,
484 2013; Bidelman et al., in press).

485 Our ERP data further imply that hearing loss might reorganize functional asymmetries at the
486 cortical level (Du et al., 2016; Pichora-Fuller et al., 2017). Source waveforms from left and right PAC
487 revealed that the normal hearing listeners showed bilateral symmetric cortical activity (Figs. 2-3). This
488 pattern was muted in listeners with mild hearing impairment, who showed faster response in right
489 hemisphere. These differences imply that the hemispheric laterality of speech undergoes a functional
490 reorganization following sensory loss where processing might be partially reallocated to right hemisphere
491 in a compensatory manner. Similar shifts in the cortical activity have been observed in sudden onset,
492 idiopathic hearing loss (He et al., 2015), implying that our results might reflect central reorganization
493 following longer-term sensory declines. Previous studies have also shown that hemispheric asymmetry is
494 correlated with SIN perception (Javad et al., 2014; Bidelman and Howell, 2016; Thompson et al., 2016).
495 Conceivably, the reduction in left hemisphere speech processing we find in hearing-impaired listeners,
496 along with reduced BS→PAC connectivity, might reflect a form of aberrant cortical function that could
497 exacerbates SIN comprehension behaviorally.

498 Our cortical ERP data contrast recent reports on senescent changes in the cortical encoding of
499 speech. Previous studies have shown larger ERP amplitudes to speech and non-speech stimuli among older
500 relative to younger listeners (Herrmann et al., 2013; Bidelman, Villafuerte, et al., 2014; Presacco et al.,
501 2016), possibly resulting from the peripheral auditory filter widening (Herrmann et al., 2013) and/or
502 decreased top-down (frontal) gating of sensory information (Chao and Knight, 1997; Peelle et al., 2011;
503 Bidelman, Villafuerte, et al., 2014). In contrast, studies reporting *larger* ERP amplitudes in older, hearing-
504 impaired adults focus nearly entirely on scalp (i.e., electrode-level) responses, which mixes temporal and
505 frontal source contributions that are involved in SIN processing in younger (Du et al., 2014; Bidelman and
506 Dexter, 2015; Bidelman and Howell, 2016; Bidelman et al., in press) and especially older adults (Du et al.,
507 2016). A parsimonious explanation of our ERP data then, is that weaker auditory cortical responses reflect
508 reduced sensory encoding (within PAC) secondary to the diminished stimulus input from hearing loss.

509 **The critical role of brainstem-cortical connectivity for degraded speech perception**

510 Our results extend previous brainstem and cortical studies by demonstrating age-related changes
511 in the neural representations within certain auditory areas but also how information is communicated
512 *between* functional levels. Notably, we found that robust feedforward neural transmission between
513 brainstem and cortex is necessary for successful SIN comprehension in older adults, particularly those
514 with mild hearing loss. To our knowledge, this is the first direct demonstration of auditory brainstem-
515 cortical connectivity in humans and how this functional reciprocity relates to complex listening skills.

516 Despite ample evidence for online subcortical modulation in animals (Suga et al., 2000; Bajo et
517 al., 2010; Slee and David, 2015; Vollmer et al., 2017), demonstrations of corticofugal effects in human

518 brainstem responses have been widely inconsistent and loosely inferred through manipulations of task-
519 related attention (Picton et al., 1971; Woods and Hillyard, 1978; Rinne et al., 2007; Skoe and Kraus,
520 2010a; Varghese et al., 2015; Forte et al., 2017). Theoretically, efferent modulation of brainstem should
521 occur only for behaviorally relevant stimuli in states of goal-directed attention (Suga et al., 2002; Slee and
522 David, 2015; Vollmer et al., 2017), and should be stronger in more taxing listening conditions (e.g.,
523 difficult SIN tasks; Krishnan and Gandour, 2009). In this regard, our assay of central connectivity during
524 online SIN identification should have represented optimal conditions to detect possible afferent-efferent
525 BS-PAC communication most relevant to behavior.

526 Our findings revealed that corticofugal (PAC→BS) efferent signaling was stronger than afferent
527 connectivity overall, implying considerable top-down processing in older adults. These results converge
528 with theoretical frameworks of aging that posit higher-level brain regions are recruited to aid speech
529 perception in older adults (Reuter-Lorenz and Cappell, 2008; Wong et al., 2009). Behaviorally, older
530 adults tend to expend more listening effort during SIN recognition than younger individuals (Gosselin and
531 Gagne, 2011). Consequently, one interpretation of our data is that the elevated, invariant PAC→BS
532 efferent connectivity we observe across the board reflects an increase in older adults' listening effort or
533 deployment of attentional resources. Such corticofugal engagement might enhance impoverished BS
534 processing that normally declines with age (Anderson, White-Schwoch, et al., 2013b; Marmel et al.,
535 2013; Bidelman, Villafuerte, et al., 2014; Clinard and Cotter, 2015; Bidelman et al., 2017), effectively
536 normalizing its output and group differences in FFR responses (e.g., Fig. 4). However, we note that
537 efferent connectivity was not associated with hearing loss or SIN performance, despite our use of an
538 active listening task. Without concomitant data from younger adults (and passive tasks) it remains unclear
539 how (if) the magnitude of corticofugal connectivity might change across the lifespan or with more
540 egregious hearing impairments. Additionally, mild cognitive impairment is known to alter brainstem and
541 cortical speech processing (Bidelman et al., 2017). As we did not measure cognitive function, it is
542 possible that at least some of group differences we observe in BS→PAC connectivity reflect undetected
543 cognitive decline, since auditory processing often covaries with cognitive function (Humes et al., 2013).

544 In stark contrast, afferent directed communication (BS→PAC) differentiated normal- and
545 hearing-impaired listeners and was more sensitive to hearing loss than corticofugal signaling. More
546 critically, afferent transmission was a strong predictor of listeners' reduced speech understanding at the
547 behavioral level and fully mediated speech-in-noise (QuickSIN) performance, above and beyond hearing
548 loss, *per se*. Said differently, we found that afferent connectivity was necessary to explain the link
549 between hearing loss (i.e., a marker of peripheral cochlear integrity) and SIN perception (behavior).
550 Simplicity of our task notwithstanding, these neurophysiological changes in cross-regional
551 communication seem to precede behavioral SIN difficulties since groups showed similar levels of

552 performance in SIN detection despite neurological variations. This agrees with notions that sensory
553 coding deficits in brainstem-cortical circuitry mark the early decline of hearing and other cognitive
554 abilities resulting from biological aging or neurotrauma (Bidelman et al., 2017; Kraus et al., 2017).

555 Our data align with previous neuroimaging studies suggesting that age-related hearing loss is
556 associated with reduced gray matter volume in auditory temporal regions (Eckert et al., 2012; Lin et al.,
557 2014), PAC volume (Husain et al., 2011; Peelle et al., 2011; Eckert et al., 2012), and compromised
558 integrity of auditory white matter tracts (Chang et al., 2004; Lin et al., 2008). Accelerated neural atrophy
559 from hearing impairment is larger in right compared to left temporal lobe (Peelle et al., 2011; Lin et al.,
560 2014). Such structural changes might account for the functional declines and redistribution of cortical
561 speech processing among our hearing-impaired cohort. Diffusion tensor imaging also reveals weaker
562 fractional anisotropy (implying reduced white matter) in the vicinity of inferior colliculus in listeners with
563 sensorineural hearing (Lin et al., 2008). These structural declines in brainstem could provide an
564 anatomical basis for the reduced functional connectivity (BS→PAC) among our hearing-impaired cohort.

565 Collectively, our findings provide a novel link between (afferent) subcortical-cortical *functional*
566 connectivity and individual differences in auditory behavioral measures related to cocktail party listening
567 (SIN comprehension). We speculate that similar individual differences in BS↔PAC connectivity strength
568 might account more broadly for the pervasive and parallel neuroplastic changes in brainstem and cortical
569 activity observed among highly experienced listeners, certain neuropathologies, and successful auditory
570 learners (Musacchia et al., 2008; Chandrasekaran et al., 2012; Bidelman, Weiss, et al., 2014; Bidelman
571 and Alain, 2015; Bidelman et al., 2017; Kraus et al., 2017; Reetzke et al., 2018). Our findings underscore
572 the importance of brain connectivity in understanding the biological basis of age-related hearing deficits
573 in real-world acoustic environments and pave the way for new avenues of inquiry into the biological basis
574 of auditory skills.

575

576 **Figure Legends**

577 **Figure 1: Audiometric and perceptual results.** (A) Audiograms for listeners with normal hearing (NH)
578 and hearing loss (HL). Hearing was ~10 dB better in NH vs. HL listeners. (B) Behavioral accuracy for
579 detecting infrequent /ta/ tokens in clear and noise-degraded conditions. Noise-related declines in
580 behavioral performance were prominent but no group differences were observed. (C) Reaction times (RTs)
581 for speech detection were similar between groups and speech SNRs. (D) HL listeners showed more
582 variability and marginally poorer QuickSIN performance than NH listeners. errorbars = \pm s.e.m., * $p < 0.05$.

583 **Figure 2: ERP (top traces) and FFR (bottom) source waveforms reflect the simultaneous encoding of**
584 **speech within cortical and brainstem tiers of the auditory system.** (A) NH listeners show a leftward
585 asymmetry in PAC responses compared to HL listeners (B), who show stronger activation in right PAC.
586 Noise weakens the cortical ERPs to speech across the board, particularly in the timeframe of P1 and N1,
587 reflecting the initial registration of sound in PAC. In contrast to cortical responses, BS FFRs are
588 remarkably similar between groups and noise conditions. Shaded regions demarcate the 100 ms speech
589 stimulus. BS, brainstem; PAC, primary auditory cortex.

590 **Figure 3: Cortical speech processing is modulated by noise interference, hearing status, and**
591 **cerebral hemisphere.** (A) P2 amplitudes are stronger in NH listeners regardless of SNR. (B) Brain
592 volumes show distributed source activation maps using Cortical Low resolution electromagnetic
593 tomography Analysis Recursively Applied (CLARA; BESA v6.1) (Jordanov et al., 2014). Functional data
594 are overlaid on the BESA brain template (Richards et al., 2016). (C) P2 latency revealed a group x
595 hemispheric interaction. In HL listeners, responses were ~3 ms earlier in right compared to left
596 hemisphere (R<L) whereas no latency differences were observed in NH ears (L=R). errorbars = \pm s.e.m.

597 **Figure 4: Brainstem speech processing as a function of noise and hearing loss.** (A) Source FFR
598 spectra for response to clear and degraded speech. Strong energy is observed at the voice fundamental
599 frequency (F0) but much weaker energy tagging the upper harmonics of speech, consistent with age-
600 related declines in high-frequency spectral coding. Group and noise-related effects in FFRs were less
601 apparent than in the cortical ERPs (cf. Fig. 3). errorbars = \pm s.e.m.

602 **Figure 5: Functional connectivity between auditory brainstem and cortex varies with hearing loss**
603 **and predicts SIN comprehension.** (A) Transfer entropy reflecting directed (casual) *afferent* neural
604 signaling from BS→PAC. Afferent connectivity is stronger in normal compared to hearing-impaired
605 listeners. (B) Afferent connectivity is weaker in listeners with poorer hearing (i.e., worse PTA thresholds)
606 and predicts behavioral SIN performance (C). Individuals with stronger BS→PAC connectivity show

607 better (i.e., lower) scores on the QuickSIN. (D) *Efferent* neural signaling from PAC→BS does not vary
608 between NH and HL listeners, suggesting similar top-down processing between groups. Similarly,
609 efferent connectivity did not covary with hearing loss (E) nor did it predict SIN comprehension (F). Solid
610 lines=significant correlations; dotted lines=*n.s.* relationships. errorbars = \pm s.e.m., *** $p < 0.001$,
611 **** $p < 0.0001$.

612 **Figure 6: Afferent neural signaling from BS to PAC fully mediates the relation between hearing**
613 **loss and SIN comprehension.** Sobel mediation analysis (Sobel, 1982) between listeners' hearing loss
614 (PTA thresholds), neural connectivity (BS→PAC signaling), and SIN comprehension (QuickSIN scores).
615 Edges show significant relations between pairwise variables identified via linear regression. (A) Hearing
616 loss by itself strongly predicts QuickSIN scores such that reduced hearing is associated with poorer SIN
617 comprehension. (B) Accounting for BS→PAC afferent connectivity renders this relation insignificant
618 (Sobel test: $z=2.42$, $p=0.016$; Sobel, 1982), indicating the strength of neural communication between BS
619 and PAC, rather than hearing loss *per se*, mediates older adults' SIN comprehension. ** $p < 0.01$,
620 *** $p < 0.001$.

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