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Cross-Sectional Associations of Peripheral Hearing, Brain Imaging, and Cognitive Performance With Speech-in-Noise Performance: The Aging and Cognitive Health Evaluation in Elders Brain Magnetic Resonance Imaging Ancillary Study

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ABSTRACT

Purpose: Population-based evidence in the interrelationships among hearing, brain structure, and cognition is limited. This study aims to investigate the cross-sectional associations of peripheral hearing, brain imaging measures, and cognitive function with speech-in-noise performance among older adults.
Method: We studied 602 participants in the Aging and Cognitive Health Evaluation in Elders (ACHIEVE) brain magnetic resonance imaging (MRI) ancillary study, including 427 ACHIEVE baseline (2018–2020) participants with hearing loss and 175 Atherosclerosis Risk in Communities Neurocognitive Study Visit 6/7 (2016–2017/2018–2019) participants with normal hearing. Speech-in-noise performance, as outcome of interest, was assessed by the Quick Speech-in-Noise (QuickSIN) test (range: 0–30; higher = better). Predictors of interest included (a) peripheral hearing assessed by pure-tone audiometry; (b) brain imaging measures: structural MRI measures, white matter hyperintensities, and diffusion tensor imaging measures; and (c) cognitive performance assessed by a battery of 10 cognitive tests. All predictors were standardized to *z* scores. We estimated the differences in QuickSIN associated with every standard deviation (*SD*) worse in each predictor (peripheral hearing, brain imaging, and cognition) using multivariable-adjusted linear regression, adjusting for demographic variables, lifestyle, and disease factors (Model 1), and, additionally, for other predictors to assess independent associations (Model 2).

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Results: Participants were aged 70–84 years, 56% female, and 17% Black. Every *SD* worse in better-ear 4-frequency pure-tone average was associated with worse QuickSIN (–4.89, 95% confidence interval, CI [–5.57, –4.21]) when participants had peripheral hearing loss, independent of other predictors. Smaller temporal lobe volume was associated with worse QuickSIN, but the association was not independent of other predictors (–0.30, 95% CI [–0.86, 0.26]). Every *SD* worse in global cognitive performance was independently associated with worse QuickSIN (–0.90, 95% CI [–1.30, –0.50]).
Conclusions: Peripheral hearing and cognitive performance are independently associated with speech-in-noise performance among dementia-free older adults. The ongoing ACHIEVE trial will elucidate the effect of a hearing intervention that includes amplification and auditory rehabilitation on speech-in-noise understanding in older adults.
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Understanding how speech is processed in demanding listening environments, such as in the presence of background noise, is fundamental to daily life, as it impacts effective communication, relationship maintenance, and participation in social activities (Glyde et al., 2011). Speech understanding is complex, involving the interplay of peripheral and central auditory functions, brain structure, and cognitive function. Speech understanding difficulties might represent the combined effects of degraded speech signals from the auditory periphery and deficits in higher-level auditory and cognitive processing (Humes & Dubno, 2010).

Difficulties understanding speech in the presence of background noise is a common complaint among older adults (Glyde et al., 2011). Older adults are often doubly challenged, experiencing both degraded auditory signals due to peripheral hearing loss and age-related changes in the neural relay processes up to and in the brain regions associated with auditory and cognitive processing (J. Y. Lee, 2015). Identifying and understanding contributors to poor speech-in-noise performance is needed to inform hearing loss treatment and intervention services tailored to individual patient needs.

Previous studies have reported the individual roles of peripheral and central auditory functions, brain structure, and cognitive function in speech-in-noise performance. Deficits in the auditory periphery are consequential but not sufficient for explaining speech understanding difficulties (Holmes & Griffiths, 2019; Phatak et al., 2019; Smith et al., 2019; Vannson et al., 2017). Brain substrates, especially temporal lobe, have been associated with speech-in-noise performance in prior literature (Armstrong, Croll, et al., 2020; Rudner et al., 2019; Tremblay et al., 2021; Wong et al., 2010). The primary auditory cortex is located in the temporal lobe and is responsible for processing auditory information for understanding. Cognitive performance, especially executive function, is important for selective attention to speech information (Billings et al., 2019; Dryden et al., 2017; S. J. Lee et al., 2018; Mukari et al., 2020; Nuesse et al., 2018; Pronk et al., 2019). However, few population-based studies have characterized the relative contribution of all three.

This study investigates cross-sectional associations of three possible contributors to speech-in-noise understanding–peripheral hearing, brain imaging measures (brain volumes, white matter microstructural integrity, and white matter hyperintensities [WMHs]) and cognitive performance—with speech-in-noise performance among older adults aged 70–84 years with hearing loss from the Aging and Cognitive Health Evaluation in Elders (ACHIEVE) baseline Visit (2018–2020) and with normal hearing from the Atherosclerosis Risk in Communities Neurocognitive Study (ARIC-NCS) Visit 6/7 (2016–2017/2018–2019).

Method

Study Population

The Atherosclerosis Risk in Communities (ARIC) study is an ongoing prospective study conducted in four U.S. communities (Forsyth County, NC; Jackson, MS; Minneapolis suburbs, MN; and Washington County, MD) since 1987 (Wright et al., 2021). All ARIC participants attending Visit 5 (2011–2013) were invited to join the ARIC-Neurocognitive Study (ARIC-NCS), with the purpose of studying the vascular contribution to dementia (Knopman et al., 2016). ARIC-NCS participants underwent a hearing assessment in 2016–2017.

The ACHIEVE study is a randomized controlled trial investigating the effect of hearing treatment versus health education control on 3-year cognitive decline (Clinicaltrials.gov identifier: NCT03243422). ACHIEVE is partially nested within ARIC-NCS and recruited 977 participants from the ARIC-NCS (n = 238) or de novo from the surrounding communities (n = 739). Older adults aged 70–84 years with untreated mild to moderate hearing loss and were free of substantial cognitive impairment (Mini-Mental

State Exam [MMSE] ≥ 23 if less than high school education; MMSE ≥ 25 if above high school), underwent baseline examination in 2018–2020, approximately corresponding to ARIC-NCS Visit 7 (2018–2019). Details of the ACHIEVE study design (Deal et al., 2018) and primary results (Lin et al., 2023) have been published previously.

The ACHIEVE Brain magnetic resonance imaging (MRI) ancillary study incorporates brain imaging into the ACHIEVE study. The study was approved by the institutional review board (IRB) of each participating study site (Johns Hopkins Bloomberg School of Public Health IRB #8773, University of Minnesota IRB #STUDY00003678, Wake Forest University Health Sciences IRB #00051699, The University of North Carolina at Chapel Hill Biomedical IRB #18–2031, and University of Mississippi Medical Center IRB #2017–0227). All participants provided written informed consent. Both ACHIEVE participants with hearing loss (n = 445) and additional ARIC-NCS participants with normal hearing (n = 208) were recruited into the ancillary study. Characteristics of the participants by cohort (i.e., by hearing loss vs. normal hearing) are presented in Supplemental Material S1.

For this analysis, we excluded eight ARIC-NCS participants not meeting the ACHIEVE inclusion criteria for comparability of age (70–84 years) and cognitive function (MMSE ≥ 23 if less than high school and ≥ 25 if above high school) between cohorts. An additional 16 participants missing speech-in-noise performance and 27 participants missing covariates were excluded, leaving a total of 602 participants. Among these participants, there were 16 participants missing brain imaging variables and two participants missing cognitive performance, so we used different analytical samples for our models. The study flowchart is presented in Figure 1.

Outcome: Speech-in-Noise Performance

Speech-in-noise performance was assessed using the Quick Speech-in-Noise (QuickSIN) test at ACHIEVE baseline (2018–2020) or ARIC-NCS Visit 6 (2016–2017; Killion et al., 2004; McArdle & Wilson, 2006; Sanchez et al., 2020). Further details of the protocols are included in Supplemental Material S2. After a practice list, participants completed two test lists (Lists 1 and 2), with six sentences in each list. Sentences in QuickSIN were designed to have few contextual cues (e.g., "The lake sparkled in the red hot sun"). Sentences were presented at 70 dB SPL in ACHIEVE and 70 dB HL in ARIC-NCS spoken by a woman, under successively increasing levels of background noise (multitalker babble simulating social gatherings in daily settings) with signal-to-noise ratio decreasing in 5-dB steps (25 [easiest], 20, 15, 10, 5, 0 [most difficult] for each sentence, respectively). Participants were instructed to repeat the sentences and to guess if unsure. Scoring was based on the correct identification of target words (5 per sentence × 6 sentences). No points were given if the participant responded with any deviation from exact target words or did not attempt to repeat. The total score of each list ranges from 0 to 30, with higher QuickSIN representing better speech-in-noise performance; scores of two test lists were averaged for analysis. The QuickSIN score was treated as a continuous variable in the primary analysis. In secondary analyses, it was analyzed as a binary variable comparing participants at the lowest (worst) quartile to participants at the top 3 quartiles to examine if the results were consistent when compared to being analyzed continuously. Further sensitivity analysis categorizing QuickSIN score based on tertiles (lowest tertile vs. top 2 tertiles) and quintiles (lowest quintiles vs. top 4 quintiles), and the results demonstrated similar inferences. To examine whether differences in the presentation level of sentences in ACHIEVE versus ARIC-NCS impact our results, we conducted sensitivity analysis excluding ACHIEVE participants with hearing loss above 50 dB HL (n = 31) and reran the models. Our inferences remained similar (pure-tone average [PTA]: see Supplemental Material S3; brain imaging: see Supplemental Material S4; cognitive performance: see Supplemental Material S5).

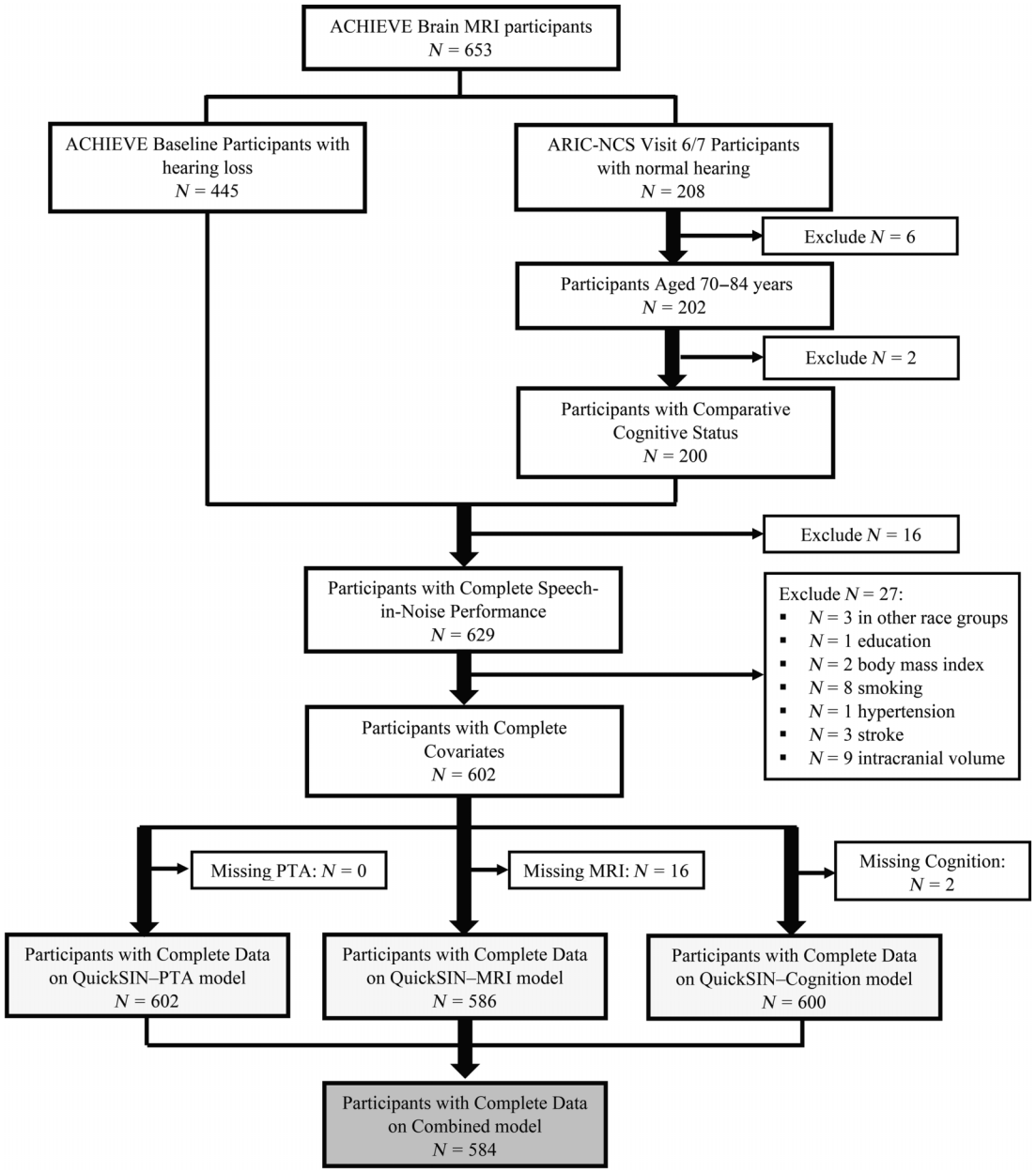
Predictor: Pure-Tone Audiometry

Pure-tone audiometry was conducted in a sound attenuating booth using an Interacoustics Equinox audiometer with insert earphones. During the test, participants were presented with pure-tone signals at 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz and instructed to respond when the signals were audible. The quietest signal participants respond for at least 50% of the time at each frequency was defined as the hearing threshold. PTAs were calculated by averaging hearing thresholds in dB HL at 0.5, 1, 2, and 4 kHz in each ear. Higher PTA indicates worse peripheral hearing. PTA in the better-hearing ear was analyzed continuously and standardized to z score (M = 0; standard deviation [SD] = 1) to facilitate comparison across models.

Predictor: Brain Imaging Variables

The ACHIEVE Brain MRI ancillary study participants (both from ACHIEVE and ARIC-NCS) completed MRI scans at ACHIEVE baseline (2018–2020). MRI scans were performed by trained technicians using 3T MRI scanners following standardized protocols at each study site. All imaging analysis was conducted by the Aging and Dementia Imaging Research Lab at the Mayo Clinic (Rochester, MN) consistent with established procedures (Jack et al., 2008, 2010). We used similar brain imaging

Figure 1. Study population, ACHIEVE baseline (2018–2020) and ARIC-NCS Visit 6/7 (2016–2017/2018–2019). ACHIEVE = Aging and Cognitive Health Evaluation in Elders; ARIC-NCS = Atherosclerosis Risk in Communities Neurocognitive Study; MRI = magnetic resonance imaging; QuickSIN = Quick Speech-in-Noise; PTA = pure-tone average.



variables as previous ARIC-NCS studies (Moazzami et al., 2020; Power et al., 2019; Wu et al., 2019).

Brain volumes were estimated based on T1-weighted magnetization-prepared rapid gradient-echo using the FreeSurfer system (Fischl, 2012). Regions of interest for analysis included total and lobar (frontal, parietal, temporal, and occipital) cortical volumes and deep gray subcortical structures (sum of insula, thalamus, caudate, putamen, and globus pallidus). Brain volumes were standardized to *z* scores with mean of 0 and *SD* of 1 and reversed (multiplying by −1) so that higher values are worse (smaller volumes). Intracranial volume was also obtained to account for variations in head size.

WMHs, ischemic changes often indicating cerebral small vessel disease, were also measured. WMH volume was quantified by T2 fluid-attenuated inversion recovery images, with higher volume indicating more WMH. Similarly, WMH volume was standardized to *z* score.

Diffusion tensor imaging was performed with diffusion weighting (b) = 1000 s/mm^2, 2.7 mm isotropic voxels and 64 encoding directions. Two measures (fractional anisotropy [FA]; mean diffusivity [MD]) were obtained to assess white matter (WM) integrity. FA measures the degree of anisotropic diffusion processes, ranging from 0 to 1. Lower FA reflects worse WM integrity. MD is a continuous measure in mm^2/s that describes diffusion rate, and higher MD indicates worse WM integrity. For analysis, FA was reversed by multiplying −1, and both FA and MD were standardized to *z* scores.

Predictor: Cognitive Performance

An identical neurocognitive test battery was administered at ACHIEVE baseline (2018–2020) or ARIC-NCS Visit 7 (2018–2019). The battery assesses three cognitive domains, including language (Animal Naming [Benton & Hamsher, 1976], Boston Naming [Williams et al., 1989], Word [phonemic] Fluency Test [Benton & Hamsher, 1976]), executive function (Trail Making Test Parts A and B [Reitan, 1958], Digit Symbol Substitution Test [Wechsler & De Lemos, 1981]), and memory (Delayed Word Recall [Knopman & Ryberg, 1989], Logical Memory [Wechsler, 1987], and Incidental Learning Test [Smith, 1968]). Global cognitive performance was summarized based on all the tests above and the Digit Span Backwards Test (Blackburn & Benton, 1957). Test scores were used to derive factor scores for global and domain-specific cognitive performance using latent variable methods described previously, as consistent with previous ARIC-NCS and ACHIEVE studies (Gross et al., 2015; Lin et al., 2023). Global and domain-specific cognitive factor scores were reversed so that higher scores represent worse cognitive performance and were standardized to *z* scores.

Other Covariates

Demographic information was collected at ACHIEVE baseline (2018–2020) or ARIC baseline (1987–1989), including birth date to calculate age in years, sex (male, female), race (White, Black), field site (Forsyth County, NC; Jackson, MS; Minneapolis, MN; and Washington County, MD), and education (below high school; high school or equivalent; above high school). Cardiovascular risk factors were collected at ACHIEVE baseline (2018–2020) or ARIC-NCS Visit 7 (2018–2019). Smoking status was self-reported as never, former, and current smoker. Body mass index (BMI) in kg/m^2 was calculated using measured height and weight. Hypertension (yes, no) was defined as systolic blood pressure ≥ 140 mm Hg, diastolic blood pressure ≥ 90 mm Hg, or self-reported use of antihypertensive medication in both cohorts. Diabetes (yes, no) was defined as fasting blood glucose level ≥ 126 mg/dL, nonfasting glucose ≥ 200 mg/dL, self-reported use of antidiabetic medication or physician diagnosis in ARIC-NCS and was based only on self-reported medication use or diagnosis for ACHIEVE participants as blood glucose level was not measured. Stroke (yes, no) was self-reported by participants before Visit 1 and was adjudicated through Visit 7 by expert review in ARIC-NCS and was self-reported at baseline in ACHIEVE.

Statistical Analysis

In descriptive analyses, participant characteristics were compared by worst versus top 3 quartiles of speech-in-noise performance status. We used *t* test (Student, 1908) for continuous variables and Pearson's chi-squared test (Pearson, 1900) for categorical variables.

Multivariable-adjusted linear regression was used to estimate differences in QuickSIN score associated with every *SD* worse in the predictor of interest. Based on graphical representation, a nonlinear association between PTA and QuickSIN was found. We included a linear spline term with a knot at the mean value of PTA (PTA = 33 dB HL, i.e., standardized PTA = 0) to allow for different linear PTA–QuickSIN relationships when PTA was below versus above the mean. Restricted cubic spline models were also explored to make sure that more flexible modeling did not significantly improve over the linear splines. In a secondary analysis examining QuickSIN as a binary variable, we used multivariable-adjusted Poisson regression with robust standard errors to estimate prevalence ratio (PR) of being in the lowest (worst) quartile of QuickSIN versus top 3 quartiles associated with every *SD* worse in the predictor. We ran regression diagnostics to check model assumptions, including linearity, normality, homoscedasticity, independence, and unusual and influential data. No significant violation of model assumptions was found. Variance inflation factor (VIF) is examined as a measure of multicollinearity and the highest VIF across our models is 3.1.

For each predictor (PTA; brain imaging variables; cognitive performance), we first estimated their individual associations with speech-in-noise performance (Model 1), adjusting for covariates including age, sex, race, field center, education, BMI, smoking, hypertension, diabetes, and stroke. Models for the brain imaging measures additionally adjusted for intracranial volume. Furthermore, to estimate the association between each predictor and speech-in-noise performance independent of other predictors (Model 2), we ran models adjusting for other predictors in addition to covariates included in Model 1.

By design, cohort is a perfect predictor of peripheral hearing loss (hearing-loss participants from ACHIEVE, normal-hearing participants from ARIC-NCS). We, therefore,

could not adjust for cohort in models including PTA. We adjusted for cohort in models without PTA as a sensitivity analysis, and the results were consistent (brain imaging: see Supplemental Material S6; cognitive performance: see Supplemental Material S7). We also further included an interaction term with cohort to examine if the associations with speech-in-noise performance differed by cohort (i.e., peripheral hearing loss) and no statistically significant differences were found (brain imaging: see Supplemental Material S8; cognitive performance: see Supplemental Material S9).

Analyses were conducted using Stata, Version 17.0 (StataCorp LLC, College Station, TX). A two-sided $p < .05$ was considered statistically significant.

Results

Our study included 602 participants (M_{age} = 77 years; 56% female; 17% Black). The mean QuickSIN score was 19 (range: 0.5–28.5). Participants in the lowest (worst) quartile (QuickSIN < 17) were less educated (below high school: 9% vs. 2%), had higher proportion of stroke (9% vs. 5%) and worse peripheral hearing (mean PTA: 42 dB HL vs. 31 dB HL) when compared to participants in the top 3 quartiles (QuickSIN ≥ 17; see Table 1).

Each *SD* (11 dB HL) worse in PTA was not associated with QuickSIN score (β = 0.12, 95% confidence interval, CI, [−0.52, 0.75]) when PTA was below the mean (< 33 dB HL) but was associated with worse QuickSIN (β = −5.16, 95% CI [−5.83, −4.50]) when PTA was above the mean (≥ 33 dB HL; see Figure 2a). When additionally adjusting for brain imaging measures and global cognitive performance, similar associations were found (PTA < 33 dB HL: β = −0.07, 95% CI [−0.71, 0.58]; PTA ≥ 33 dB HL: β = −4.89, 95% CI [−5.57, −4.21]; see Figure 2b). Consistent results were found when modeling QuickSIN categorically (see Supplemental Material S10). Each *SD* increase in PTA was associated with higher prevalence of being in the worst quartile of QuickSIN (PR = 2.38, 95% CI [1.94, 2.93]) and was robust to adjustment for other predictors (PR = 2.34, 95% CI [1.88, 2.90]) when PTA was above the mean (≥ 33 dB HL).

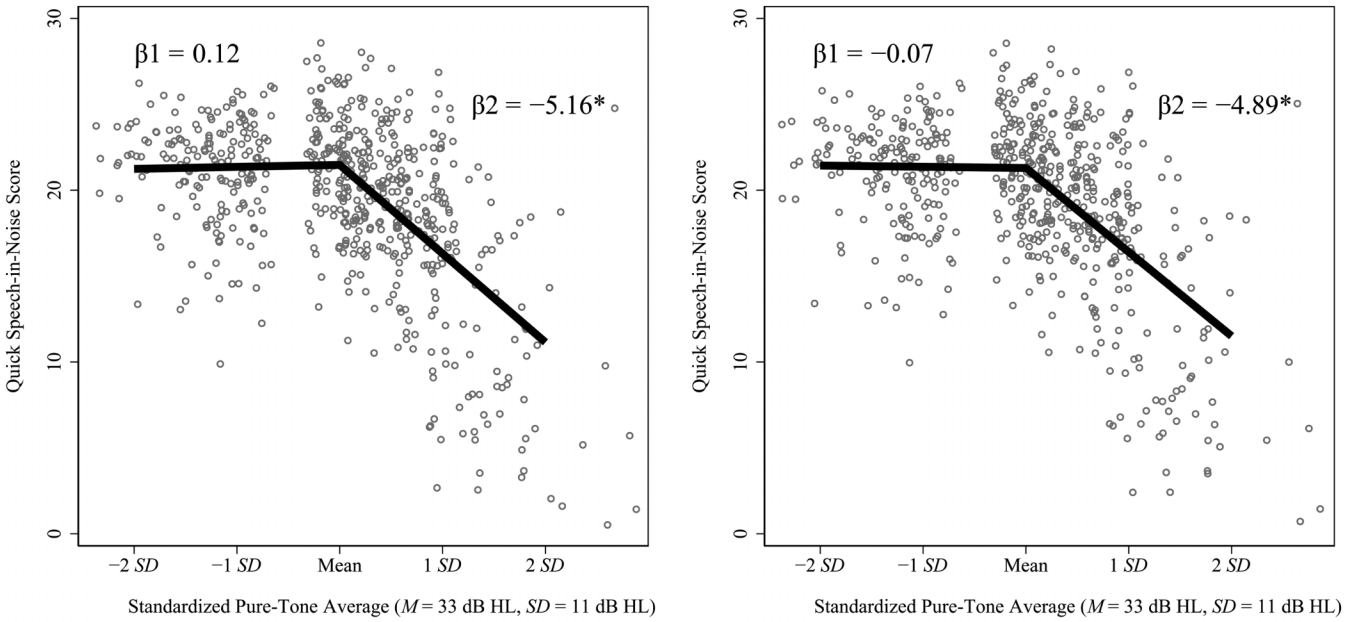
Table 1. Characteristics of participants by speech-in-noise performance at ACHIEVE baseline (2018–2020) and ARIC-NCS Visit 6/7 (2016–2017/2018–2019).

Variable	Total *N* = 602	Speech-in-noise performance[a]		*p* value[b]
		Top 3 quartiles *n* = 470	Lowest quartile *n* = 132	
Age (years), *M* (*SD*)	76.8 (3.9)	76.7 (3.9)	77.0 (4.0)	.47
Female, *n* (%)	338 (56.1)	271 (57.7)	67 (50.8)	.16
Black, *n* (%)	104 (17.3)	84 (17.9)	20 (15.2)	.46
Education, *n* (%)				< .001
Below high school	23 (3.8)	11 (2.3)	12 (9.1)	
High school or equivalent	260 (43.2)	175 (37.2)	85 (64.4)	
Above high school	319 (53.0)	284 (60.4)	35 (26.5)	
Cigarette smoking, *n* (%)				.38
Never	289 (48.0)	220 (46.8)	69 (52.3)	
Former	291 (48.3)	234 (49.8)	57 (43.2)	
Current	22 (3.7)	16 (3.4)	6 (4.5)	
Body mass index (kg/m^2), *M* (*SD*)	28.9 (5.4)	28.7 (5.5)	29.6 (5.2)	.09
Hypertension, *n* (%)	422 (70.1)	326 (69.4)	96 (72.7)	.46
Diabetes, *n* (%)	132 (21.9)	101 (21.5)	31 (23.5)	.62
Stroke, *n* (%)	34 (5.6)	22 (4.7)	12 (9.1)	.05
Pure-tone average[c] (dB HL), *M* (*SD*)	33.1 (11.4)	30.7 (10.2)	42.0 (10.9)	< .001
QuickSIN score, *M* (*SD*)	19.3 (4.9)	21.4 (2.6)	11.9 (4.3)	< .001
Cohort, *n* (%)				< .001
ACHIEVE	427 (70.9)	310 (66.0)	117 (88.6)	
ARIC-NCS	175 (29.1)	160 (34.0)	15 (11.4)	

Note. QuickSIN = Quick Speech-in-Noise; ACHIEVE = Aging and Cognitive Health Evaluation in Elders; ARIC-NCS: Atherosclerosis Risk in Communities Neurocognitive Study.

[a]The Quick Speech-in-Noise test is a test of speech-in-noise performance. Total scores range from 0 to 30 with lower scores indicating worse speech-in-noise performance. The continuous score was categorized according to quartiles and a binary variable was further constructed as top 3 quartiles (≥ 17) versus lowest quartile (< 17). [b]*p* values were calculated by *t* test for continuous variables and Pearson chi-squared test for categorical variables. [c]Pure-tone average was calculated by averaging hearing thresholds at 0.5, 1, 2, and 4 kHz in the better hearing ear and higher pure-tone average indicates worse peripheral hearing.

Figure 2. Multivariable-adjusted associations of pure-tone average with speech-in-noise performance, the Aging and Cognitive Health Evaluation in Elders baseline (2018–2020) and the Atherosclerosis Risk in Communities Neurocognitive Study Visit 6/7 (2016–2017/2018–2019): Multivariable-adjusted linear regression with spline term at mean pure-tone average (PTA), which is 33 dB HL (standardized PTA = 0) to estimate change in the quick speech-in-noise score associated with every standard deviation worse in PTA when PTA < 33 dB HL and PTA ≥ 33 dB HL, respectively. (a) Model adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, and stroke (N = 602). (b) Model adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, stroke, intracranial volume, global cognitive performance, total brain volume, fractional anisotropy, mean diffusivity, and white matter hyperintensities volume (n = 584). *p < .05.



For brain imaging measures, we found an association for temporal lobe volume, where every *SD* worse temporal lobe volume was associated with 0.82-point (95% CI [0.16, 1.49]) worse QuickSIN score (see Table 2, Model 1). Other brain volumes, WM integrity measures (FA and MD) and WMH were not associated with QuickSIN. Adjusting for PTA (β = −0.54, 95% CI [−1.09, 0.02]) or global cognitive performance (β = −0.56, 95% CI [−1.23, 0.11]) alone showed similar level of attenuation of the association between temporal lobe volume and speech-in-noise performance (see Supplemental Material S11). The association was attenuated more markedly by adjustment of both predictors (β = −0.30, 95% CI [−0.86, 0.26]; see Table 2, Model 2). Results remained consistent with categorical QuickSIN as the outcome (see Supplemental Material S12).

For cognitive performance, every *SD* worse global (β = −0.97, 95% CI [−1.43, −0.50]) and domain-specific (language: β = −0.71, 95% CI [−1.17, −0.26]; executive function: β = −0.75, 95% CI [−1.22, −0.28]; memory: β = −0.44, 95% CI [−0.85, −0.03]) cognitive performance were associated with worse QuickSIN score (see Table 3, Model 1). Additional adjustment for PTA and brain imaging measures showed similar results (see Table 3, Model 2). When modeling QuickSIN categorically, every *SD* worse global cognitive performance (PR = 1.25, 95% CI [1.04, 1.49]) and executive function (PR = 1.20, 95% CI [1.01, 1.43]) were associated with higher prevalence of being in the worst quartile of QuickSIN score but not with language and memory (see Supplemental Material S13).

Discussion

In this cross-sectional study of 602 community-dwelling older adults free of dementia (70–84 years; 56% female; 17% Black), each *SD* (11 dB HL) increase in PTA was associated with identifying ~5 fewer target words on the QuickSIN test among individuals with hearing loss above the mean (33 dB HL). This association was independent of brain imaging markers and cognitive performance, suggesting PTA's impact on speech-in-noise performance is not solely through brain and cognitive changes. Each *SD* worse global and domain-specific cognitive performance was also independently associated with a 0.5 to 1 word poorer speech-in-noise score. A summary of study findings is presented in Supplemental Material S14. Taken together, our findings suggest that clinical

Table 2. Multivariable-adjusted associations of magnetic resonance imaging measures with speech-in-noise performance, the Aging and Cognitive Health Evaluation in Elders baseline (2018–2020) and the Atherosclerosis Risk in Communities Neurocognitive Study Visit 6/7 (2016–2017/2018–2019).

Worse MRI measures, per *SD*[a]	Model 1: Covariates (*n* = 586)[b]		Model 2: Covariates + other predictors (*n* = 584)[c]	
	Estimate [95% CI]	*p* value	Estimate [95% CI]	*p* value
Brain volumes				
Total brain	–0.01 [–0.93, 0.92]	.99	0.25 [–0.52, 1.02]	.53
Temporal lobe	–0.82 [–1.49, –0.16]	.02	–0.30 [–0.86, 0.26]	.29
Frontal lobe	–0.31 [–1.00, 0.38]	.38	–0.22 [–0.79, 0.35]	.45
Occipital lobe	–0.05 [–0.63, 0.53]	.86	0.06 [–0.42, 0.54]	.81
Parietal lobe	–0.16 [–0.85, 0.53]	.64	0.14 [–0.42, 0.71]	.62
Deep gray subcortical structures	–0.30 [–0.84, 0.25]	.28	–0.12 [–0.57, 0.33]	.59
Fractional anisotropy	0.06 [–0.43, 0.55]	.81	0.14 [–0.26, 0.54]	.50
Mean diffusivity	–0.05 [–0.46, 0.35]	.79	0.13 [–0.21, 0.47]	.44
White matter hyperintensities volume	–0.27 [–0.67, 0.13]	.18	–0.14 [–0.47, 0.20]	.42

Note. MRI = magnetic resonance imaging; *SD* = standard deviation; CI = confidence interval.

[a]Multivariable-adjusted linear regression to estimate change in the quick speech-in-noise score associated with every *SD* worse in brain MRI measures. [b]Model 1 adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, stroke, and intracranial volume. [c]Model 2 adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, stroke, intracranial volume, pure-tone average, and global cognitive performance.

interventions to improve speech-in-noise in older adults might consider a combination of hearing amplification device use and rehabilitation to address the multiple possible contributors to speech-in-noise understanding. Given the design of the hearing rehabilitation intervention in ACHIEVE, the study is well poised to test this hypothesis in a randomized controlled design (Lin et al., 2023).

Speech-in-noise performance relies on both peripheral encoding and higher-level decoding of auditory information (Humes & Dubno, 2010). Peripheral hearing, characterized by pure-tone audiometry, primarily reflects initial cochlear encoding of the auditory signals. It is therefore not surprising to find that peripheral hearing is a strong predictor of speech-in-noise performance, suggesting that the most common reason for deficits in speech-in-noise understanding among community-dwelling older adults free of dementia is impaired peripheral hearing contributing to poor transduction of auditory stimuli in the cochlea (Helfer & Freyman, 2008). This finding supports current clinical practices of recommending hearing devices that ensure speech signals are audible to the patient through amplification to aid speech-in-noise concerns.

We found an association between peripheral hearing and speech-in-noise performance only among participants with hearing loss above the mean PTA of 33 dB HL. The cut point observed is consistent with degree of hearing loss that is most likely to benefit from hearing devices, indicating a group to be prioritized (Humes, 2019; Olusanya et al., 2019). However, this finding should be interpreted with caution as we did not have participants with PTA between 25 and 30 dB HL by design, resulting in a limited number of participants near the cut point. Future studies

Table 3. Multivariable-adjusted associations of global and domain-specific cognitive performance with speech-in-noise performance, the Aging and Cognitive Health Evaluation in Elders baseline (2018–2020) and the Atherosclerosis Risk in Communities Neurocognitive Study Visit 6/7 (2016–2017/2018–2019).

Worse cognitive performance, per *SD*[a]	Model 1: Covariates (*n* = 600)[b]		Model 2: Covariates + other predictors (*n* = 584)[c]	
	Estimate [95% CI]	*p* value	Estimate [95% CI]	*p* value
Global	–0.97 [–1.43, –0.50]	< .001	–0.90 [–1.30, –0.50]	< .001
Language	–0.71 [–1.17, –0.26]	.002	–0.85 [–1.24, –0.46]	< .001
Executive function	–0.75 [–1.22, –0.28]	.002	–0.68 [–1.09, –0.27]	.001
Memory	–0.44 [–0.85, –0.03]	.03	–0.48 [–0.82, –0.13]	.01

Note. CI = confidence interval.

[a]Multivariable-adjusted linear regression to estimate change in the quick speech-in-noise score associated with every *SD* worse in cognitive performance. [b]Model 1 adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, and stroke. [c]Model 2 adjusted for age, sex, race, field center, education, body mass index, smoking, hypertension, diabetes, stroke, intracranial volume, pure-tone average, total brain volume, fractional anisotropy, mean diffusivity, and white matter hyperintensities volume.

with greater representation across the hearing loss spectrum would address this limitation. It is also important to acknowledge that, although peripheral hearing did not on average predict speech-in-noise performance among participants with normal to mild hearing loss, people may have speech-in-noise deficits with normal or near-normal audiometry; in our study, 15 (2%) participants in the worst quartile of speech-in-noise performance had normal audiometric hearing (Smith et al., 2019). Clinically, hearing evaluation based solely on pure-tone audiometry is not adequate for capturing hearing function (Phatak et al., 2019).

Importantly, our study found an independent contribution of cognitive function to speech-in-noise performance, particularly for executive function. Cognitive resources can aid in interpretation and understanding of auditory signals based on contextual information (Peelle, 2018). Our findings support the importance of working memory for speech-in-noise understanding, which requires the ability to selectively processing relevant auditory information while inhibiting irrelative background noise and temporally storing the auditory information to repeat back (Ben-David et al., 2012; Rimmele et al., 2015; Rönnberg et al., 2010, 2013). This finding suggests that auditory rehabilitation and training techniques, in addition to amplification of sound, may prove important components of addressing auditory needs among older adults.

As the primary auditory cortex lies in the temporal lobe, consistent with previous studies (Lin et al., 2014; Rudner et al., 2019), we found smaller temporal lobe volumes associated with poorer speech-in-noise performance. We did not find associations with other brain imaging measures reported by previous studies. The prefrontal cortex might be engaged in the speech-in-noise performance (Holmes et al., 2021; Wong et al., 2010). WM integrity reflects anatomical connectivity that is important for integration of auditory information (Armstrong, Croll, et al., 2020; Armstrong, Williams, et al., 2020; Schmithorst et al., 2011). Additionally, the presence of WMHs indicates pathological small vessel disease that might impair brain structure and function for central auditory processing (Alber et al., 2019; Eckert et al., 2013; Knopke et al., 2021). It is possible that longitudinal changes in brain imaging markers, in contrast to brain imaging markers measured at a single time point in this study, are more important to speech-in-noise performance. Our study population with a mean age of 77 years is also relatively older than previous studies.

However, we did not find that temporal lobe volume is an independent predictor of speech-in-noise performance when adjusting for peripheral hearing and/or cognitive performance. This finding is not surprising, given that peripheral hearing loss is a risk factor for temporal lobe atrophy (Lin et al., 2014), which in turn could lead to poorer speech-in-noise understanding. In other words, if temporal lobe atrophy is a consequence of hearing loss, adjustment for PTA would attenuate the observed temporal lobe-QuickSIN association. Similarly, given that neurodegeneration leads to cognitive decline (Kaup et al., 2011), adjustment for cognitive test performance (as a mediator) would attenuate the temporal lobe-QuickSIN association. Taken together, peripheral hearing loss may impact speech-in-noise performance through temporal lobe atrophy or cognitive impairments, but our findings suggest that not all its effect is through these pathways. Future longitudinal analysis is needed to clarify these pathways.

Our study aims to examine how peripheral hearing, brain imaging measures, and cognitive performance predict speech-in-noise performance individually and independently of each other, in order to identify the strongest predictor(s), as well as potential clinical targets to improve speech-in-noise performance. Our study is limited in that our analysis is cross-sectional with predictors and outcome assessed at the same time; we therefore cannot establish temporality. However, ongoing follow-up of the ACHIEVE brain MRI ancillary study will enable future longitudinal analysis to link baseline predictors with changes in speech-in-noise performance. Future analysis will also consider a large set of brain imaging measures to disentangle the contribution of different brain regions. Also, the comparability of hearing-loss (from ACHIEVE) and normal-hearing (from ARIC-NCS) participants needs to be carefully considered. Although we have applied the ACHIEVE inclusion criteria regarding age and cognition and additionally adjusted for cohort in sensitivity analyses, the two groups differ in age distribution (ARIC-NCS: 73–85 years, M = 79; ACHIEVE: 70–84 years, M = 76), so residual confounding is a possible concern.

Our study also has strengths. ARIC-NCS and ACHIEVE are multicenter studies of diverse community-dwelling older adults and might be more generalizable to the general older adult population when compared to smaller clinical samples. We also had a modest sample size with a set of well-measured predictors, including pure-tone audiometry, brain imaging, and a neurocognitive test battery to comprehensively evaluate their contribution to speech-in-noise performance.

Conclusions

In a diverse cohort of dementia-free older adults, peripheral hearing and cognitive performance were important predictors of speech-in-noise performance. Hearing amplification devices together with rehabilitation services might benefit older adults' daily communications. The

ongoing ACHIEVE study will provide further insights into the effects of best practice hearing intervention with aspects of auditory rehabilitation on speech-in-noise performance.

Data Availability Statement

Researchers can request data from the ARIC or ACHIEVE Data Coordinating Center.

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