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Original Contribution

Hearing Impairment and Cognitive Decline: A Pilot Study Conducted Within the Atherosclerosis Risk in Communities Neurocognitive Study

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Hearing impairment (HI) is prevalent, is modifiable, and has been associated with cognitive decline. We tested the hypothesis that audiometric HI measured in 2013 is associated with poorer cognitive function in 253 men and women from Washington County, Maryland (mean age = 76.9 years) in a pilot study carried out within the Atherosclerosis Risk in Communities Neurocognitive Study. Three cognitive tests were administered in 1990–1992, 1996–1998, and 2013, and a full neuropsychological battery was administered in 2013. Multivariable-adjusted differences in standardized cognitive scores (cross-sectional analysis) and trajectories of 20-year change (longitudinal analysis) were modeled using linear regression and generalized estimating equations, respectively. Hearing thresholds for pure tone frequencies of 0.5–4 kHz were averaged to obtain a pure tone average in the better-hearing ear. Hearing was categorized as follows: ≤25 dB, no HI; 26–40 dB, mild HI; and >40 dB, moderate/severe HI. Comparing participants with moderate/severe HI to participants with no HI, 20-year rates of decline in memory and global function differed by −0.47 standard deviations ($P = 0.02$) and −0.29 standard deviations ($P = 0.02$), respectively. Estimated declines were greatest in participants who did not wear a hearing aid. These findings add to the limited literature on cognitive impairments associated with HI, and they support future research on whether HI treatment may reduce risk of cognitive decline.

aging; cognition; cognitive decline; hearing impairment; memory; perbycussis

Abbreviations: ARIC, Atherosclerosis Risk in Communities; CES-D, Center for Epidemiologic Studies Depression Scale; CI, confidence interval; DSST, Digit Symbol Substitution Test; DWRT, Delayed Word Recall Test; HI, hearing impairment; SD, standard deviation.

Recent epidemiologic studies have indicated that hearing impairment (HI) may be a risk factor for cognitive decline (1–3). HI is highly prevalent in older adults and may be amenable to rehabilitative interventions (4, 5).

The association between hearing loss and cognitive impairment could be explained if both conditions are sequelae of an underlying pathology (e.g., vascular disease, inflammation). Alternatively, mechanistic hypotheses have been proposed that argue for a causal association between HI and cognitive decline, including increased social isolation and loneliness, increased cognitive load, and changes in brain structure (6).

In prior studies, audiometric HI has been associated cross-sectionally with test-specific cognitive performance in several cognitive domains (memory, executive function, and global function) in older adults (1, 2) and in a longitudinal analysis with faster rates of decline in global function and executive attention over 6 years of follow-up (3). Data on the use of hearing aids in these studies have been limited.

We used data from a pilot study carried out in a subset of participants from the Atherosclerosis Risk in Communities (ARIC) Study to test the hypothesis that, compared with participants without HI, participants with HI in older age have poorer cognitive performance as measured by multiple cognitive tests, both cross-sectionally at the time when hearing is measured and longitudinally, with a faster rate of 20-year change in cognitive function measured from midlife to older age.

The effect of correcting HI on cognitive decline is unknown but is important for public health efforts designed to prevent cognitive decline in older adults. We hypothesized that, among participants with HI (i.e., among participants who would potentially benefit from HI correction), participants who use hearing aids have slower rates of cognitive decline than participants with HI who do not use hearing aids. Therefore, we repeated the analyses restricting the data to only those participants with moderate or severe HI in order to quantify the association of hearing aid use with cognitive decline.

METHODS

Study population

The ARIC Study is a population-based prospective cohort study of 15,792 men and women aged 45–64 years recruited in 1987–1989 from 4 US communities (Washington County, Maryland; Forsyth County, North Carolina; Jackson, Mississippi; and Minneapolis, Minnesota). ARIC participants returned for a fifth ARIC visit in 2011–2013 (the ARIC Neurocognitive Study). A pilot study on hearing was initiated at the Washington County field site in 2013, and audiometric testing was offered to 307 ARIC participants at their regularly scheduled ARIC visit. Six declined participation, and 46 did not complete the examination (45 of them because of compacted cerumen in one or both ears). Since only 2 participants were nonwhite, analysis was restricted to self-reported whites, resulting in an analytical sample of 253. Compared with other ARIC 2011–2013 participants, participants in the hearing pilot study were older (77.1 (standard deviation (SD), 5.4) years vs. 75.7 (SD, 5.3) years; $P < 0.01$) and more likely to have a high school education or less (60% vs. 46%; $P < 0.01$). Participants in the pilot study who were included in our analysis scored higher on the Wide Range Achievement Test (45.5 (SD, 6.1) vs. 42.9 (SD, 8.0); $P = 0.04$) and trended toward a lower proportion with less education (60% vs. 67%; $P = 0.31$). Informed consent was obtained from all participants at each study visit.

Cognitive outcomes

Cross-sectional measures. A comprehensive neuropsychological battery was administered in 2013. Standardized test scores were used to create summary cognitive-domain scores in the following domains: 1) *memory*—Delayed Word Recall Test (DWRT) (7), Incidental Learning Test (8), and Logical Memory Test I and II (9); 2) *language*—Word Fluency Test (10), Animals Naming Test (11), and Boston Naming Test (12); and 3) *processing speed/attention*—Digit Symbol Substitution Test (DSST) (13), Digit Span Backwards Test (13), and Trail Making Test Parts A and B (14, 15). Scores on the Trail Making Test Parts A and B were transformed to the natural log values to account for nonnormality. All test scores were standardized to z scores, and arithmetic signs were changed for the Trail Making tests so that higher scores indicated better function for all tests. All test-specific z scores were then averaged within each domain to yield a domain-specific score. A global cross-sectional composite score was created by averaging the 3 domain-specific z scores. In order to facilitate comparisons, the global composite score and each domain score were then scaled so that 1 unit equaled 1 SD of that score.

Most of these cognitive tests included both auditory and written stimuli. Two tests that administer only auditory stimuli, the Logical Memory Test and the Digit Span Backwards Test, were excluded from the domain-specific summary scores in sensitivity analyses.

Longitudinal measures. Three neuropsychological tests representing the different cognitive domains—memory (DWRT), language (Word Fluency Test), and processing speed/attention (DSST)—were administered 3 times, in 1990–1992, 1996–1998, and 2013. For longitudinal analyses, the z scores for these tests at each testing occasion were scaled to their mean and the SD on first testing at baseline (1990–1992). Consistent with previous studies in this cohort (16, 17), the sum of the 3 test-specific z scores was used to create a global longitudinal composite score that was then scaled to the baseline SD of that global score.

Hearing assessment

Pure tone air conduction audiometry was conducted in a sound-treated booth in 2013. Air conduction thresholds in each ear were obtained at standard octaves from 0.5 kHz to 8 kHz by trained technicians using insert earphones (EARTone 3a; 3M, St. Paul, Minnesota) and an Interacoustics AD629 audiometer (Interacoustics A/S, Assens, Denmark). All thresholds were measured in decibels of hearing level. For each participant, the threshold levels for the pure tone frequencies of 0.5 kHz, 1 kHz, 2 kHz, and 4 kHz in the better-hearing ear were averaged to obtain a pure tone average in accordance with the World Health Organization (18). We categorized pure tone average according to clinically defined cutpoints for HI (normal: ≤25 dB; mild: 26–40 dB; moderate/severe: >40 dB); because only 5 participants had severe HI (>70 dB), moderate and severe HI were combined to create 1 category.

Hearing aid use was defined as self-reported use of a hearing aid in either ear during the previous month.

Other independent variables

Demographic information was collected in 1987–1989, including age (years), sex, and education (highest grade or year of school completed). Education was categorized for analysis as ≤12 years and >12 years.

Self-reported information on current and past cigarette smoking was collected at each study visit and coded as ever or never for analysis. Hypertension (19) was considered present if diastolic blood pressure was greater than or equal to 90 mm Hg, systolic blood pressure was greater than or equal to 140 mm Hg, or the participant took hypertensive medication. Diabetes (19) was defined as fasting blood glucose level ≥126 mg/dL, nonfasting blood glucose level ≥200 mg/dL, or self-reported physician's diagnosis of diabetes or use of medication for diabetes.

Depressive symptoms were measured in 1990–1992 using 7 items that relate to depression from the 21-item Maastricht Questionnaire, which assesses vital exhaustion (20). Responses to these items (0 = no, 1 = don't know, and 2 = yes) were summed to yield a possible score ranging from 0 to 14, with higher scores indicating higher levels of depressive symptoms. Depressive symptomatology in 2013 was measured using the 11-item Center for Epidemiologic Studies Depression Scale (CES-D) (21). Possible 11-item CES-D scores range from 0 to 22, with an observed range in this sample of 0–15; higher scores indicate greater depressive symptomatology. Given the absence of clinical depression (CES-D scores were less than 16 for all participants) and because the distribution of CES-D scores in this sample was highly skewed, for analysis CES-D scores were categorized at the median value of the distribution (≤3 vs. ≥4).

Statistical analysis

Multivariable linear regression was used to estimate the average cross-sectional difference in cognitive test performance in 2013, comparing persons with and without HI.

For the longitudinal analysis, in order to account for the correlation between repeated cognitive measures in an individual over time, generalized estimating equations (22) with an unstructured correlation matrix and robust variance were used to estimate the difference in the estimated average trajectories of cognitive change over time (1990–2013) according to HI status as measured in 2013. An interaction term for the interaction between HI and time was included in the models in order to test whether rates of cognitive change over time differed by hearing status. Time since baseline was used as the time scale. A 2-piece linear spline with a knot at year 6 was included in the model in order to allow for differential rates of cognitive change before and after year 6. Year 6 was chosen a priori as the knot for the spline on the basis of the ARIC study design: 6 years was the mean follow-up time between baseline and the second round of cognitive testing (1996–1998), after which there was a subsequent 16-year gap until cognitive testing was performed in 2013. Model fit was good, as assessed using residual plots, the Bayesian Information Criterion, and the Akaike Information Criterion.

Models were adjusted for demographic and disease covariates that were measured in 1987–1989, including education and sex. Time-varying covariates, including age, smoking status, hypertension, and diabetes, were measured at baseline for the longitudinal analysis or in 2013 for the cross-sectional analysis. All analyses also adjusted for scores on the Wide Range Achievement Test, a measure of premorbid intelligence, administered in 2013. Age was modeled using both linear (years) and quadratic ($years^2$) components. Because depression could be a possible mediator of the relationship between HI and cognitive performance, we did not adjust for depression in our primary model. In a sensitivity analysis, we repeated the analyses with adjustment for depressive symptoms.

To evaluate the association of hearing aid use with cognitive performance, we repeated the analyses after restricting the data to persons with moderate or severe HI.

RESULTS

Of 253 participants, 73 (29%) had no HI, 95 (37%) had mild HI, and 85 (34%) had moderate or severe HI. Mean age at the time of the hearing assessment was 76.9 (SD, 5.4) years, and 58.9% of participants had a high school education or less. On average, participants with moderate/severe HI were older (79.4 years) and more likely to be male (54%) and to have hypertension at baseline (33%) than participants with mild or no HI (Table 1).

Mean test scores across categories of HI differed in 2013 for some (but not all) tests of memory (DWRT, Incidental Learning Test), language (Animal Naming Test, Boston Naming Test), and processing speed/executive function (DSST). DWRT and DSST scores also differed at baseline. A dose-response relationship between HI category and performance on each of these tests was suggested; mean test scores were poorest for participants with moderate/severe HI and best for participants with no HI. We did not observe a difference in mean test scores by HI category in tests that used only auditory stimuli (the Logical Memory Test and the Digit Span Backwards Test), which may reflect administration of all tests in a quiet room by technicians trained to work with older adults (Table 2).

Compared with participants with no HI, participants with mild HI showed poorer concurrent memory domain performance (−0.35 SDs, 95% confidence interval (CI): −0.62, −0.07; $P = 0.01$) in cross-sectional analysis (see model 1 in Web Table 1, available at http://aje.oxfordjournals.org/). When cognitive tests that include only auditory stimuli (Logical Memory Test and Digit Span Backwards Test) were excluded from the cognitive domain summary scores, we observed significant differences in memory performance for both moderate/severe HI and mild HI: −0.39 SDs (95% CI: −0.70, −0.07) and −0.37 SDs (95% CI: −0.65, −0.08), respectively (Web Table 1, model 3). Inferences did not change after adjustment for depressive symptoms (Web Table 1, models 2 and 4).

Observed mean scores by HI status on each of the 3 cognitive testing occasions are presented in Figure 1. There is the suggestion of a dose-response relationship between HI category and cognitive decline. After adjustment for demographic and disease covariates, on average, cognitive performance in all domains declined for all 3 HI groups during the approximately 20 years of follow-up (Table 3, Figure 2). Compared with participants with no HI, participants with moderate/severe HI declined at a faster rate on the DWRT and the global composite score; comparing the 2 groups, the average difference in the rate of 20-year decline was −0.47 SDs (95% CI: −0.86, −0.08) for the DWRT and −0.29 SDs (95% CI: −0.54, −0.05) for the global composite score. Further adjustment for depressive symptoms did not change the estimates (Web Table 2).

Among the 85 participants with moderate/severe HI, 51% ($n = 43$) reported using a hearing aid (Table 1). Compared with hearing aid users, nonusers were more likely to have hypertension (45% vs. 21% at baseline ($P = 0.02$) and 83% vs. 70% in 2013 ($P = 0.14$)) and diabetes (14% vs. 7% at baseline ($P = 0.31$) and 48% vs. 33% in 2013 ($P = 0.16$)). Duration of hearing aid use varied across participants and ranged from less than 1 year to 48 years (Table 1). In multivariable-adjusted analyses among participants with moderate/severe HI, not using a hearing aid was associated with poorer cross-sectional performance in memory (−0.74 SDs, 95% CI: −1.16, −0.32),

Table 1. Characteristics of Study Participants by Hearing Impairment Status, Atherosclerosis Risk in Communities Neurocognitive Study ($n = 253$), 1990–2013

Characteristic	Total Cohort ($n = 253$)		Presence of HI[a]								No HI ($n = 73$)		P Value[b]
			Moderate/Severe HI ($n = 85$)						Mild HI ($n = 95$)				
			Total ($n = 85$)		No Hearing Aid Use ($n = 42$)		Hearing Aid Use ($n = 43$)						
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
Age, years[c]													
1990–1992 (baseline)	56.6 (5.3)		59.1 (5.4)		59.1 (5.4)		59.3 (5.0)		56.4 (4.9)		53.8 (4.0)		0.0001
2013	76.9 (5.4)		79.4 (5.7)		79.4 (5.7)		79.8 (6.0)		76.8 (4.9)		74.0 (4.2)		0.0001
High school education or less[d]	149	58.9	51	60.0	27	64.3	24	55.8	56	59.0	42	57.5	0.952
Male sex[d]	99	39.1	46	54.1	20	47.6	26	60.5	37	39.0	16	21.9	<0.0001
Ever smoker													
1990–1992 (baseline)	112	44.3	41	48.2	17	40.5	24	55.8	41	43.2	30	41.1	0.642
2013	122	48.2	44	51.8	19	45.2	25	58.1	45	47.4	33	45.2	0.697
Diabetes													
1990–1992 (baseline)	19	7.5	9	10.6	6	14.3	3	7.0	7	7.4	3	4.1	0.305
2013	86	34.0	34	40.0	20	47.6	14	32.6	32	33.7	20	27.4	0.248
Hypertension													
1990–1992 (baseline)	59	23.3	28	32.9	19	45.2	9	20.9	18	19.0	13	17.8	0.036
2013	182	71.9	65	76.5	35	83.3	30	69.8	64	67.4	53	72.6	0.394
Depressive symptoms[e,f]													
1990–1992 (baseline)	2 (0–4)		2 (0–4)		2 (0–4)		2 (0–4)		2 (0–4)		2 (0–4)		0.792
2013	3 (1–5)		3 (1–6)		3.5 (1–5)		3 (1–7)		2 (1–5)		3 (1–5)		0.295
Wide Range Achievement Test[c,g,h]	45.5 (6.1)		44.4 (6.0)		44.7 (5.7)		44.2 (6.4)		46.2 (5.9)		45.7 (6.2)		0.137
Hearing level (pure tone average), dB[c,h]	35.2 (15.2)		52.1 (9.6)		49.6 (8.7)		54.5 (9.8)		33.2 (4.1)		18.1 (6.3)		
Hearing aid use[h,i]	52	20.6	43	50.6	0	0.0	43	100.0	6	6.3	3	4.1	<0.0001
Duration of hearing aid use, years[f,h,j]							4 (2–10)		3 (2–4)		7 (1–12)		0.808

Abbreviation: HI, hearing impairment.

[a] HI was defined as none (≤25 dB), mild (26–40 dB), or moderate/severe (>40 dB).

[b] For continuous variables, *P* value from 1-way analysis of variance or a Kruskall-Wallis test comparing mean/median cognitive test scores across categories of HI (moderate/severe, mild, none); for categorical variables, *P* value from Pearson's χ^2 test.

[c] Values are expressed as mean (standard deviation).

[d] Measured in 1987–1989.

[e] Score was based on 7 questions from the 21-item Maastricht Questionnaire, administered in 1990–1992 (possible range, 0–14), and the 11-item Center for Epidemiologic Studies Depression Scale, administered in 2013 (possible range, 0–22).

[f] Values are expressed as median and interquartile range (25th–75th percentiles).

[g] A measure of premorbid intelligence.

[h] Measured in 2013 only.

[i] Defined as self-reported hearing aid use in either ear during the previous month.

[j] The ranges of duration of hearing aid use were 0.5–48 years, 1–15 years, and 1–12 years for participants with moderate/severe HI ($n = 43$), mild HI ($n = 6$), and no HI ($n = 3$) who reported hearing aid use, respectively.

Table 2. Distributional Characteristics of Cognitive Test Scores by Domain, Atherosclerosis Risk in Communities Neurocognitive Study ($n = 253$), 1990–2013[a]

Domain and Cognitive Test	Units/Interpretation	Total Cohort ($n = 253$)	Presence of HI[b]		No HI ($n = 73$)	*P* Value[c]
			Moderate/Severe HI ($n = 85$)	Mild HI ($n = 95$)		
Memory						
Delayed Word Recall Test	No. of words correctly recalled					
1990–1992 (baseline)		7.1 (1.3)	6.9 (1.3)	7.0 (1.4)	7.5 (1.1)	0.013
2013		5.5 (1.7)	4.9 (1.8)	5.6 (1.5)	6.2 (1.7)	<0.0001
Incidental learning[d]	No. of symbols/digit-pairs recalled in 60 seconds	3.7 (2.4)	3.4 (2.2)	3.4 (2.4)	4.5 (2.5)	0.006
Logical memory[d]	No. of elements recalled in 2 trials	20.3 (6.9)	20.0 (7.1)	19.5 (7.0)	21.7 (6.6)	0.111
Language						
Word Fluency Test	No. of words generated in 3 trials					
1990–1992 (baseline)		36.0 (11.1)	35.2 (11.7)	35.5 (10.9)	37.7 (10.6)	0.399
2013		33.3 (11.4)	31.3 (12.1)	34.0 (11.0)	34.8 (10.9)	0.117
Animal Naming Test[d]	No. of animals named in 60 seconds	16.5 (4.5)	15.8 (4.7)	16.3 (4.4)	17.6 (4.3)	0.033
Boston Naming Test[d]	No. of pictures identified	26.4 (3.8)	25.4 (5.0)	26.9 (2.4)	26.8 (3.4)	0.017
Processing speed/executive function						
Digit Symbol Substitution Test	No. of symbols completed in 90 seconds					
1990–1992 (baseline)		51.4 (9.5)	48.9 (9.7)	51.7 (8.6)	53.8 (9.8)	0.007
2013		40.3 (9.8)	36.8 (9.2)	41.1 (9.3)	43.4 (9.9)	0.0001
Digit Span Backwards Test[d]	No. of sequences recalled	5.8 (1.7)	5.7 (1.7)	6.0 (1.8)	5.7 (1.7)	0.576
Trail Making Test Part A[d,e,f]	Time to completion (seconds); lower scores indicate better performance	36 (27–43)	34 (25–48)	38 (29–43)	36 (28–41)	0.616
Trail Making Test Part B[d,e,f]	Time to completion (seconds); lower scores indicate better performance	106 (76–145)	111 (81–165)	107 (77–133)	95 (73–135)	0.122

Abbreviation: HI, hearing impairment.
[a] Values are expressed as mean (standard deviation) unless otherwise noted.
[b] HI was defined as none (≤25 dB)), mild (26–40 dB), or moderate/severe (>40 dB).
[c] *P* value from 1-way analysis of variance or a Kruskal-Wallis test comparing mean/median cognitive test scores across categories of HI.
[d] Measured only in 2013.
[e] Higher scores indicate better performance for all cognitive tests except the Trail Making Test Parts A and B, for which lower scores indicate better performance.
[f] Values are expressed as median and interquartile range (25th–75th percentiles).

language (−0.78 SDs, 95% CI: −1.20, −0.36), and global function (−0.64, 95% CI: −1.03, −0.24) (Web Table 3). Estimated average 20-year changes were greater for hearing aid nonusers than for hearing aid users in memory (−0.95 SDs, 95% CI: −1.53, −0.38) and global function (−0.48 SDs, 95% CI: −0.83, −0.14) (Table 4).

DISCUSSION

In this pilot study, carried out among 253 white ARIC Neurocognitive Study participants from Washington County, Maryland (mean age = 77 years), our results demonstrated that moderate/severe HI measured in late life was associated with poorer concurrent memory performance and with a faster rate of prior 20-year decline in both memory and global cognitive function. Although, on average, all participants with moderate/severe HI declined in all 3 domains, the greatest decline was estimated for participants who reported not using a hearing aid. The estimated 20-year rate of decline in memory for this group was −1.84 SDs (95% CI: −2.28, −1.39), which was −0.95 SDs (95% CI: −1.53, −0.38) faster than the estimated rate for persons with the same degree of HI who reported wearing a hearing aid. Notably, the global decline in persons with moderate/severe HI who used hearing aids (−0.97; Table 4) was only slightly greater than the corresponding decline in persons with normal hearing (−0.90; Table 3).

For our longitudinal analysis, HI was not measured until the end of follow-up for cognitive function. Therefore, one possible interpretation of our findings is that cognitive decline leads to HI (i.e., reverse causation), either from indirect effects of cognitive impairment on the accuracy of hearing assessment or from direct effects of neuropathology which contributes to cognitive impairment (e.g., microvascular disease, accumulation of amyloid β and τ protein) also affecting the peripheral auditory system. However, pure tone audiometry is considered a measure of the auditory periphery (not dependent on higher-order auditory or cognitive processing (23)), and valid hearing thresholds can be obtained even in participants with dementia (24). Neuropathology associated with

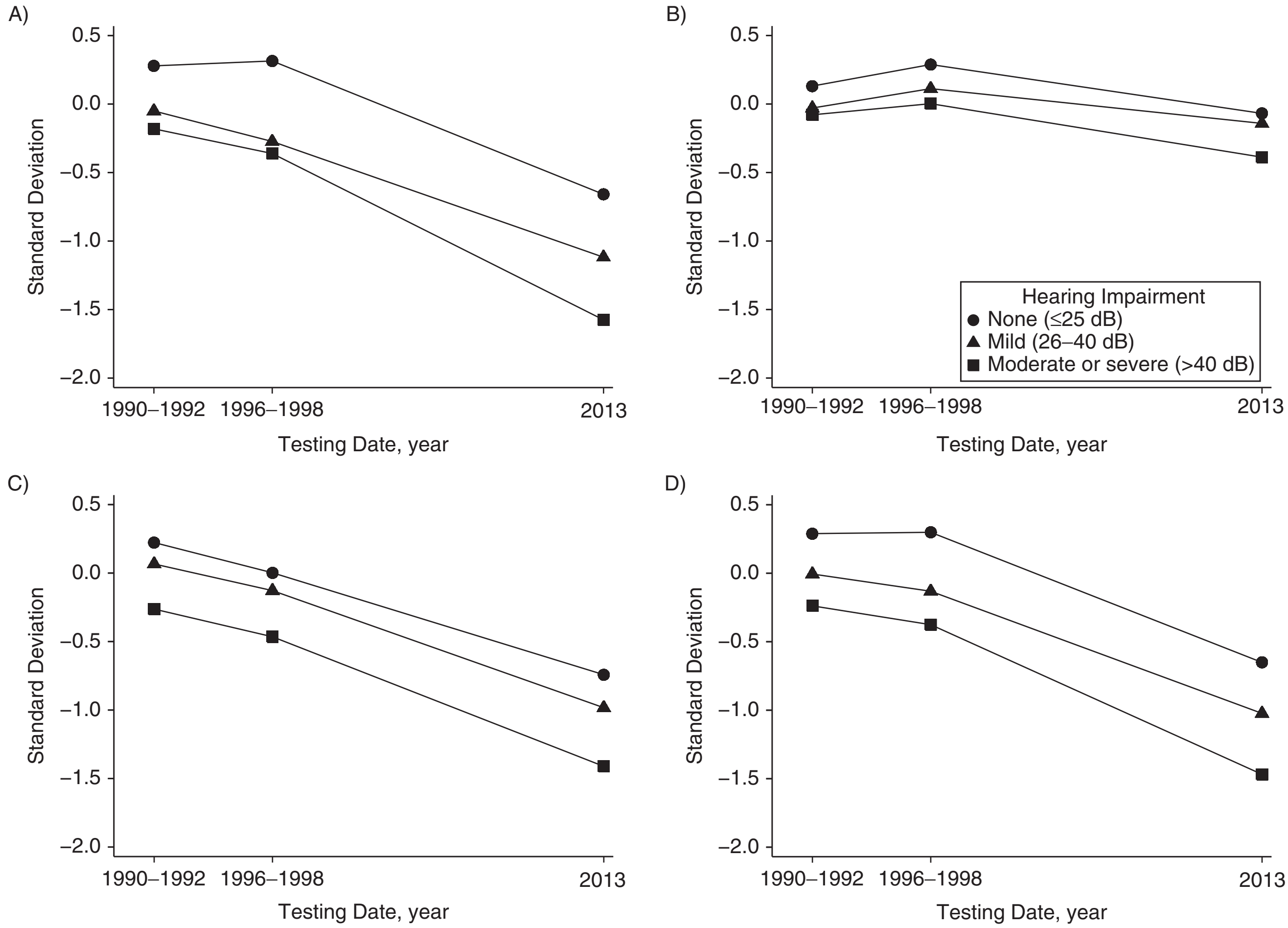

Figure 1. Mean standardized cognitive test scores observed over time, by hearing impairment status, among participants in the Atherosclerosis Risk in Communities Neurocognitive Study ($n = 253$), 1990–2013. A) Delayed Word Recall Test; B) Word Fluency Test; C) Digit Symbol Substitution Test; D) global longitudinal composite score. Hearing impairment was measured in 2013.

Alzheimer's disease has also not been found in the peripheral auditory pathways (25, 26), and we adjusted for multiple midlife and late-life cardiovascular risk factors in our analyses. Regardless, we cannot rule out the possibility that the observed association between HI and cognitive decline is due to an unmeasured factor that causes both conditions, although this limitation is true for any observational epidemiologic study.

A number of mechanisms could account for the observed association between HI and poorer cognitive functioning. Persons with HI may perform more poorly on tests of cognitive function because they are unable to hear test administrators. However, although all cognitive tests require that the participants hear the instructions, cognitive testing was routinely performed in a quiet room by technicians highly experienced in working with older adults, and we also observed strong associations of HI with both auditory and nonauditory cognitive tests.

HI has also been hypothesized to be a causal risk factor for cognitive decline and dementia through several mechanisms that are not mutually exclusive: increased social isolation and loneliness, increased cognitive load, and changes in brain structure. Social isolation is associated with physiological changes, such as increases in systolic blood pressure and increased glucocorticosteroid levels, which could in turn impact brain structure, and several epidemiologic studies have demonstrated an association between social isolation and accelerated cognitive decline and dementia (27). In a recent cross-sectional analysis of data from the National Health and Nutrition Examination Survey, HI was associated with increased odds (odds ratio = 3.49, 95% CI: 1.91, 6.39) of social isolation in women aged 60–69 years (28). Poor or impaired encoding by the cochlea may require extra cognitive processing effort, limiting the effort available for encoding the content of speech into memory. This increase in cognitive load due to HI has been termed *effortful listening* (29, 30). Additionally, neuroimaging studies have suggested that structural changes within the brain may occur in response to HI, both cross-sectionally (31) and longitudinally (32). For example, in 126 participants aged 56–86 years from the Baltimore Longitudinal Study of Aging, HI was longitudinally associated with a faster rate of atrophy

Table 3. Longitudinal, Multivariable-Adjusted[a] Estimates of Rates of Cognitive Change and Differences Between Estimated Rates of Cognitive Change by Hearing Impairment Status,[b] Atherosclerosis Risk in Communities Neurocognitive Study ($n = 253$), 1990–2013

Cognitive Test and HI Category	Rate of Change								
	Years 1–5 (per 6 Years)			Years 6–23 (per 6 Years)			20-Year Change		
	β[c]	95% CI	*P* Value	β[c]	95% CI	*P* Value	β[d]	95% CI	*P* Value
Delayed Word Recall Test									
HI category									
Moderate/severe	−0.19	−0.41, 0.04	0.107	−0.50	−0.61, −0.39	<0.0001	−1.35	−1.66, −1.05	<0.0001
Mild	−0.22	−0.43, −0.01	0.038	−0.34	−0.44, −0.25	<0.0001	−1.02	−1.24, −0.80	<0.0001
None	0.03	−0.17, 0.24	0.741	−0.39	−0.51, −0.27	<0.0001	−0.88	−1.13, −0.64	<0.0001
Difference (mild HI vs. none)	−0.25	−0.54, 0.04	0.086	0.05	−0.11, 0.20	0.521	−0.14	−0.47, 0.20	0.411
Difference (moderate/severe HI vs. none)	−0.22	−0.56, 0.04	0.155	−0.11	−0.27, 0.05	0.186	−0.47	−0.86, −0.08	0.018
Word Fluency Test									
HI category									
Moderate/severe	0.06	−0.06, 0.19	0.310	−0.16	−0.23, −0.09	<0.0001	−0.31	−0.47, −0.15	<0.0001
Mild	0.16	0.03, 0.28	0.016	−0.11	−0.16, −0.06	<0.0001	−0.10	−0.23, 0.03	0.126
None	0.13	0.001, 0.26	0.048	−0.13	−0.19, −0.08	<0.0001	−0.17	−0.30, −0.03	0.015
Difference (mild HI vs. none)	0.02	−0.16, 0.21	0.802	0.02	−0.06, 0.10	0.614	0.07	−0.12, 0.26	0.463
Difference (moderate/severe HI vs. none)	−0.07	−0.25, 0.11	0.451	−0.03	−0.11, 0.06	0.507	−0.14	−0.35, 0.07	0.198
Digit Symbol Substitution Test									
HI category									
Moderate/severe	−0.21	−0.35, −0.08	0.002	−0.37	−0.43, −0.32	<0.0001	−1.09	−1.24, −0.93	<0.0001
Mild	−0.19	−0.31, −0.07	0.002	−0.35	−0.41, −0.29	<0.0001	−1.01	−1.13, −0.88	<0.0001
None	−0.19	−0.31, −0.07	0.002	−0.31	−0.36, −0.26	<0.0001	−0.92	−1.07, −0.77	<0.0001
Difference (mild HI vs. none)	0.001	−0.17, 0.17	0.987	−0.04	−0.12, 0.04	0.356	−0.09	−0.28, 0.11	0.377
Difference (moderate/severe HI vs. none)	−0.02	−0.20, 0.16	0.801	−0.06	−0.14, 0.02	0.117	−0.17	−0.38, 0.05	0.124
Global longitudinal composite score									
HI category									
Moderate/severe	−0.16	−0.30, −0.01	0.031	−0.45	−0.51, −0.38	<0.0001	−1.20	−1.38, −1.02	<0.0001
Mild	−0.12	−0.24, 0.01	0.060	−0.37	−0.43, −0.30	<0.0001	−0.97	−1.11, −0.83	<0.0001
None	−0.02	−0.13, 0.10	0.793	−0.38	−0.45, −0.31	<0.0001	−0.90	−1.08, −0.74	<0.0001
Difference (mild HI vs. none)	−0.10	−0.27, 0.07	0.249	0.02	−0.08, 0.11	0.746	−0.06	−0.28, 0.15	0.570
Difference (moderate/severe HI vs. none)	−0.14	−0.33, 0.04	0.133	−0.06	−0.16, 0.03	0.176	−0.29	−0.54, −0.05	0.019

Abbreviations: CI, confidence interval; HI, hearing impairment.

[a] Adjusted for age (years), age^2 (years^2), sex, education (high school or less vs. more than high school), smoking status (ever smoking vs. never smoking), diabetes (fasting blood glucose concentration ≥126 mg/dL or participant self-report and medication use for diabetes), hypertension (diastolic blood pressure ≥90 mm Hg, systolic blood pressure ≥140 mm Hg, or use of hypertensive medication), and Wide Range Achievement Test score.

[b] HI was measured in 2013 and was defined as none (≤25 dB)), mild (26–40 dB), or moderate/severe (>40 dB). Numbers of participants with no HI, mild HI, and moderate/severe HI were 73, 95, and 85, respectively.

[c] Estimate was scaled to 6 years so that the interpretation is the estimated rate of cognitive change per 6 years.

[d] Estimate combines rates of change before and after year 6 to give an overall estimate of the rate of cognitive change over 20 years.

in the right temporal lobe (for participants with HI vs. participants without HI, difference in estimated average annual rate of change = −0.29 cm^3, 95% CI: −0.54, −0.04), as well as with whole brain atrophy (estimated average difference in annual rate of change associated with HI = 1.20 cm^3, 95% CI: −2.17, −0.22) (32).

Although estimates were imprecise because of the small sample size, the estimated rate of 20-year memory decline in persons with moderate/severe HI who did not report wearing a hearing aid was large—about twice the average annual rate of change estimated in nationally representative studies of cognitive change in older adults (33, 34). However,

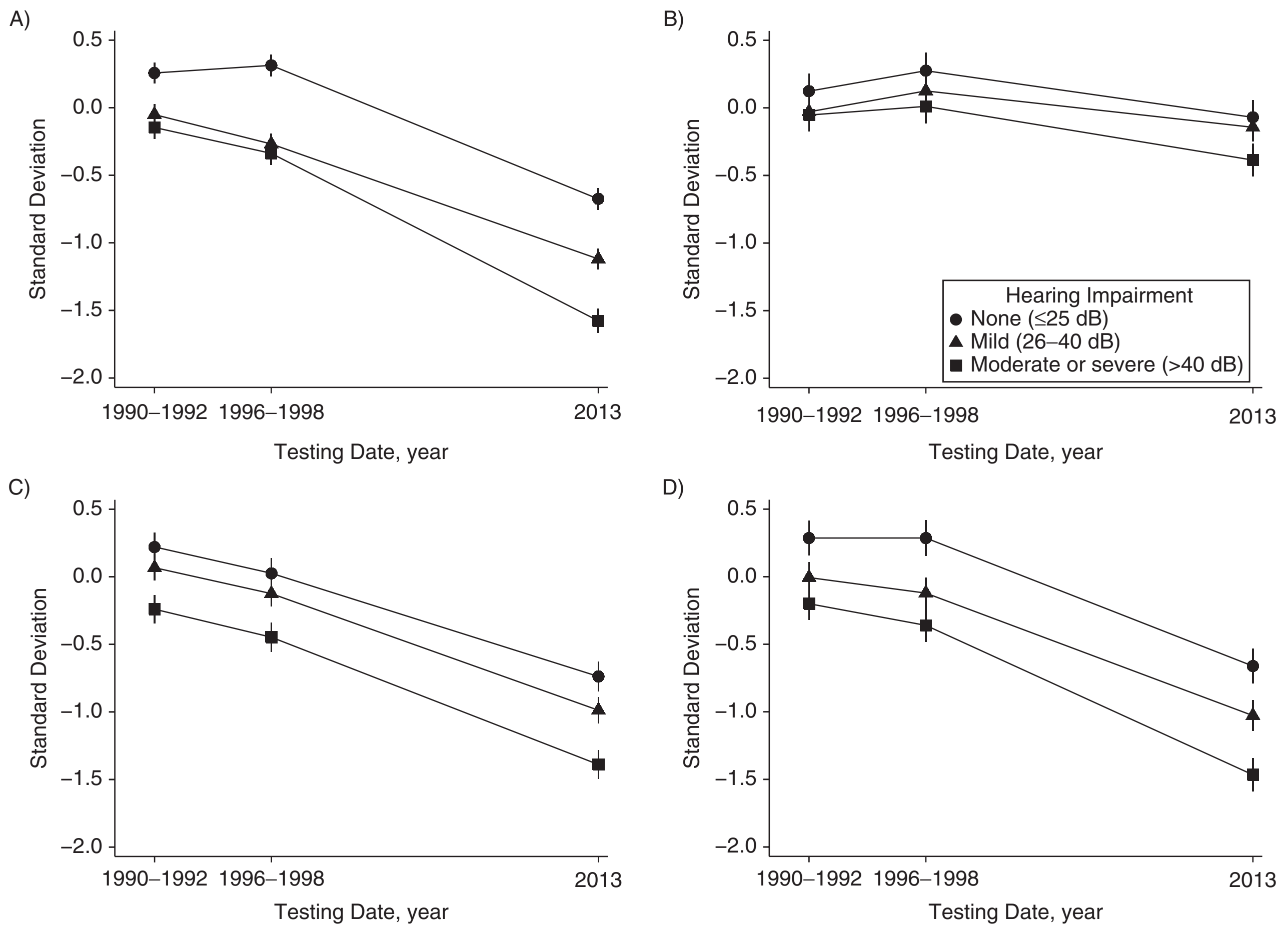

Figure 2. Multivariable-adjusted estimates of mean standardized cognitive test scores over time, by hearing impairment status, Atherosclerosis Risk in Communities Neurocognitive Study ($n = 253$), 1990–2013. A) Delayed Word Recall Test; B) Word Fluency Test; C) Digit Symbol Substitution Test; D) global longitudinal composite score. Estimates were adjusted for age (years), age^2 (years^2), sex, education (high school or less vs. more than high school), smoking status (ever smoking vs. never smoking), diabetes (fasting blood glucose concentration ≥126 mg/dL or participant self-report and medication use for diabetes), hypertension (diastolic blood pressure ≥90 mm Hg, systolic blood pressure ≥140 mm Hg, or use of hypertensive medication), and Wide Range Achievement Test score. Hearing impairment was measured in 2013.

residual confounding may still have affected the longitudinal differences we observed in rates of cognitive decline between hearing aid users and nonusers. Nonusers in our sample had more comorbidity (hypertension, diabetes) at a younger age than did persons with the same amount of HI who reported wearing a hearing aid. Given that hearing aids are not currently covered by Medicare and the average cost of a pair of hearing aids is more than $2,000, hearing aid use could also be a marker of better socioeconomic status and education and therefore increased access to health care and/or a more healthy lifestyle. However, education is not associated with cognitive decline in this cohort (16), and other stable socioeconomic characteristics seem unlikely to influence measures of change in cognition. Data on other key variables (e.g., duration of hearing aid use, adequacy of hearing aid fitting and rehabilitation) that would affect the success of hearing loss treatment and affect any observed association were also not accounted for in our analyses. Nevertheless, although we cannot determine causality from this study, the slower rate of estimated decline in hearing aid users as compared with nonusers is intriguing and should be the focus of further study.

Investigators in 2 previous studies of older adults reported an association between HI and poorer performance on the DSST. Cross-sectionally, HI was associated with a DSST score difference of −1.5 points (95% CI: −2.9, −0.23) among 605 men and women in the National Health and Nutrition Examination Survey (1). In a longitudinal analysis of 1,984 older adults (mean age = 77.4 years) from the Health, Aging, and Body Composition Study, HI was associated with faster rates of decline on the Modified Mini-Mental State Examination ($P = 0.004$)—a test of global function—and on the DSST ($P = 0.02$) over 6 years of follow-up (3). In our study, we observed faster rates of decline on the Delayed Word Recall Test—a word list learning task—and in global function, but not on the DSST. In a recent analysis of the Baltimore Longitudinal Study of Aging cohort, Lin et al. (2) reported cross-sectional associations between HI and poorer cognitive function in several domains, including memory (Free and

Table 4. Longitudinal, Multivariable-Adjusted[a] Estimates of Rates of Cognitive Change and Differences Between Estimated Rates of Cognitive Change, by Hearing Aid Use,[b] Among Participants With Moderate/Severe Hearing Impairment in 2013 ($n = 85$), Atherosclerosis Risk in Communities Neurocognitive Study, 1990–2013

Cognitive Test and Hearing Aid Use	Rate of Change								
	Years 1–5 (per 6 Years)			Years 6–23 (per 6 Years)			20-Year Change		
	β[c]	95% CI	*P* Value	β[c]	95% CI	*P* Value	β[d]	95% CI	*P* Value
Delayed Word Recall Test									
No hearing aid use	−0.41	−0.74, −0.09	0.012	−0.61	−0.79, −0.43	<0.0001	−1.84	−2.28, −1.39	<0.0001
Hearing aid use	0.02	−0.30, 0.33	0.913	−0.39	−0.49, −0.28	<0.0001	−0.89	−1.25, −0.52	<0.0001
Difference (no use – use)	−0.43	−0.88, 0.02	0.061	−0.22	−0.43, −0.01	0.037	−0.95	−1.53, −0.38	0.001
Word Fluency Test									
No hearing aid use	0.04	−0.15, 0.22	0.694	−0.18	−0.29, −0.07	0.001	−0.38	−0.66, −0.10	0.008
Hearing aid use	0.09	−0.07, 0.25	0.275	−0.14	−0.22, −0.06	0.001	−0.24	−0.41, −0.07	0.007
Difference (no use – use)	−0.05	−0.30, 0.19	0.676	−0.04	−0.17, 0.10	0.586	−0.14	−0.47, 0.19	0.404
Digit Symbol Substitution Test									
No hearing aid use	−0.29	−0.47, −0.10	0.002	−0.38	−0.47, −0.29	<0.0001	−1.18	−1.14, −0.93	<0.0001
Hearing aid use	−0.15	−0.35, 0.05	0.139	−0.37	−0.44, −0.30	<0.0001	−1.00	−1.19, −0.82	<0.0001
Difference (no use – use)	−0.14	−0.41, 0.13	0.319	−0.01	−0.13, 0.10	0.814	−0.17	−0.48, 0.13	0.274
Global longitudinal composite score									
No hearing aid use	−0.31	−0.52, −0.09	0.005	−0.49	−0.59, −0.39	<0.0001	−1.45	−1.70, −1.20	<0.0001
Hearing aid use	−0.02	−0.21, 0.17	0.833	−0.41	−0.48, −0.33	<0.0001	−0.97	−1.21, −0.74	<0.0001
Difference (no use – use)	−0.28	−0.57, 0.003	0.052	−0.08	−0.21, 0.04	0.184	−0.48	−0.83, −0.14	0.006

Abbreviation: CI, confidence interval.

[a] Adjusted for age (years), age^2 (years^2), sex, education (high school or less vs. more than high school), smoking status (ever smoking vs. never smoking), diabetes (fasting blood glucose concentration ≥126 mg/dL or participant self-report and medication use for diabetes), hypertension (diastolic blood pressure ≥90 mm Hg, systolic blood pressure ≥140 mm Hg, or use of hypertensive medication), and Wide Range Achievement Test score.

[b] Hearing aid use was measured in 2013 and was defined as self-reported use of a hearing aid in either ear during the previous month. Numbers of participants who reported using a hearing aid and not using a hearing aid were 43 and 42, respectively.

[c] Estimate was scaled to 6 years so that the interpretation is the estimated rate of cognitive change per 6 years.

[d] Estimate combines rates of change before and after year 6 to give an overall estimate of the rate of cognitive change over 20 years.

Cued Selective Reminding Test), executive function (Stroop Test), and global function (Mini-Mental State Examination). They reported no association with 2 tests of language (Animal and Category Fluency) and with the Trail Making Test Parts A and B, which is similar to our results. Previous studies have also shown an association between HI and incident dementia. In 1,057 men from the Caerphilly Prospective Study, audiometric HI was associated with increased odds of incident dementia over 17 years of follow-up (odds ratio = 2.67, 95% CI: 1.38, 5.18) (35), and in 639 participants aged 36–90 years in the Baltimore Longitudinal Study of Aging, baseline HI was associated with increased risk of all-cause dementia over approximately 12 years of follow-up (per 10-dB loss, hazard ratio = 1.27, 95% CI: 1.06, 1.50) (36). Our study adds to the literature on HI and cognition in older adults through the inclusion of multiple tests to measure several cognitive domains, and it adds to the small but growing body of literature on HI and domain-specific cognitive function.

Our results are limited in their generalizability, given that our study consisted only of whites from Washington County, Maryland. Additionally, we did not have data on duration of HI. Although our exposure was not measured until the end of follow-up for cognitive function, longitudinal analyses of cognitive change avoid the potentially strong cross-sectional confounding effects of variables like education and other factors associated with social disadvantage (16).

In conclusion, this study documented a moderate association between moderate/severe HI and memory performance, both at the time of hearing testing and over the prior 20 years, in 253 white men and women from Washington County, Maryland. This association was strongest among persons with moderate/severe HI who reported not wearing a hearing aid. These findings lend support to the hypothesis that HI may be a risk factor for cognitive decline in older adults and that hearing aid use could possibly reduce that risk. HI is highly prevalent among older adults, and although it is amenable to rehabilitative devices and interventions, these interventions remain underutilized. Given the current lack of treatments for altering the natural history of cognitive decline and dementia, further research is needed as to whether HI interventions could reduce cognitive decline in older adults.

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