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Cognitive Functions in Adult Cochlear Implant Users, Cochlear Implant Candidates, and Normal-Hearing Listeners

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Objectives: Increasing evidence suggests that hearing loss may be linked to cognitive decline, and that cochlear implantation may lead to improvements in cognition. The goal of this study was to examine the effects of severe-to-profound hearing loss and cochlear implantation in post-lingually deafened adults, compared with age-matched normal-hearing (NH) peers. Participants were tested on several non-auditory measures of cognition: working memory (WM) (digit span, object span, symbol span), non-verbal reasoning (Raven's progressive matrices), information-processing speed and inhibitory control (Stroop test), speed of phonological and lexical access (Test of Word Reading Efficiency), and verbal learning and memory (California Verbal Learning Test). Demographic measures were also collected.

Methods: Cohort study at tertiary neurotology center. Forty-three post-lingually deafened experienced CI users, 19 post-lingually deafened CI candidates, and 40 age-matched NH controls with no cognitive impairment were enrolled. Comparisons among the groups on the cognitive measures were performed.

Results: Adult CI users and CI candidates demonstrated worse (or a trend towards worse) performance as compared with NH peers on non-verbal reasoning, information-processing speed, speed of lexical access, and verbal learning and memory. However, after controlling for gender, socioeconomic status (SES), and vocabulary knowledge among groups, some of these differences were no longer significant. Similarly, large differences were not found in most cognitive abilities between experienced CI users and CI candidates.

Conclusions: Adult CI users, CI candidates, and NH peers generally demonstrated equivalent non-auditory cognitive abilities, after controlling for gender, SES, and vocabulary knowledge. These findings provide support for a link between cognitive decline and hearing loss, but this association may be partly attributable to group differences in SES and vocabulary knowledge.

Key Words: Dementia, hearing loss, cognitive decline, cochlear implant.

Level of Evidence: 2b.

INTRODUCTION

Hearing loss and dementia are two of the most prominent challenges facing healthcare. One-third of individuals over the age of 65 years have disabling age-related hearing loss, defined as pure tone average (500, 1000, and 2000 Hz) greater than 40 dB.[1] As the percentage of the American population over age 65 increases, the incidence of presbycusis will increase as well. Likewise, dementia, a progressive decline in cognitive function, is estimated to affect 47 million people worldwide—a number projected to triple by 2050.[2]

Over the past 20 years, significant efforts have been devoted to identifying a link between hearing loss and cognitive dysfunction.[3–5] A recent systematic review identified 17 studies, each of which suggested at least a weak correlation between age-related hearing loss and dementia.[6] If hearing loss contributes to cognitive decline, then hearing restoration may represent a modifiable risk factor to ameliorate cognitive decline. Indeed, two recent longitudinal reports of cochlear implantation (CI) in individuals over the age of 65 have demonstrated improved cognitive function following implantation.[7,8] Hearing aid use also appears to have a positive impact on cognition, although rigorous studies are still needed.[9–11]

The underlying mechanisms explaining the relationship between hearing loss and cognitive (dys)function remain unclear.[12] Humes and Young performed a thorough review of research studies examining how individuals with hearing loss perform on cognitive tasks.[13] Individuals with hearing loss were found to perform worse

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than normal-hearing (NH) peers; however, many studies have used auditory tasks to assess cognitive function, which increases the risk of bias due to impaired audibility. Additionally, age itself is a risk factor for both auditory processing deficits and cognitive declines, which may complicate any interpretation of the link between hearing loss and cognition.[14]

To our knowledge, no studies have directly compared non-auditory cognitive abilities among NH individuals, post-lingually deafened adult CI users, and adults with hearing loss who are CI candidates. Examining groups from these latter two populations of patients with hearing loss may provide insight into the effects of hearing loss on cognition, because these individuals typically suffer substantial hearing loss for a prolonged period of time prior to implantation. In particular, it is possible that living with severe-to-profound hearing loss results in potentially reversible cognitive impairment, even with CI. On the other hand, as suggested in the earlier studies reviewed above, it is possible that restoration of auditory input with a CI may improve cognitive function to the level of NH individuals, providing support for the theory that rehabilitating hearing may mitigate the risk of cognitive decline.

The present study was carried out to investigate performance on non-auditory cognitive tasks by post-lingually deafened experienced CI (ECI) users, NH peers, and a small group of CI candidates (CICs) who were tested preoperatively on the same battery of tests. Non-auditory tasks were chosen to avoid the confounding effects of differences in hearing abilities and speech processing impairments, which are known to be highly variable among CI users and CI candidates. Subjects were matched as groups based on age, because aging is well established as a risk factor contributing to differences in cognitive functions. Socioeconomic status (SES) and vocabulary knowledge were also included because of their possible associations with cognitive functioning. Three hypotheses were tested: 1) ECI users would demonstrate relative deficits in non-auditory cognitive processes compared with age-matched NH peers, which could be attributed to their experience with a prolonged severe-to-profound hearing loss prior to implantation; 2) CICs would also demonstrate relative deficits in these cognitive processes, when compared with NH controls; and 3) ECI users would demonstrate better cognitive processing when compared with CI candidates, which could be attributed to restoration of hearing and their rehabilitative experience with a CI. In summary, we expected to see the best performance on cognitive tests by NH controls, the poorest cognitive performance by CI candidates, and intermediate levels of cognitive performance by ECI users.

MATERIALS AND METHODS

Participants

Forty-three post-lingually deafened ECI users, 40 NH individuals, and 19 adults with bilateral severe-to-profound hearing loss who met the clinical criteria to be classified as CICs were enrolled. All ECI participants and CICs experienced post-lingual deafness during childhood or adulthood. All ECI users were implanted after age 18 years. Etiologies of hearing loss in ECI users were genetic (41.9%), progressive loss (39.5%), ototoxicity (7.0%), unknown (9.3%), and Meniere's disease (2.3%). All ECI participants had greater than 18 months of CI experience and demonstrated CI-aided thresholds better than 35 dB HL at 0.25, 0.5, 1, and 2 kHz, as measured by clinical audiologists within 12 months prior to enrollment in the current study. Mean better-ear unaided four-tone pure-tone average (PTA) at 0.5, 1, 2, and 4 kHz for ECI users was 98.7 dB HL (*SD* 17.9). All ECI users had Cochlear devices (Sydney, Australia), and used an Advanced Combined Encoder speech processing strategy, except for one patient who had an Advanced Bionics device (Valencia, California) and used a HiRes 120 processing strategy. Seventeen (39.5%) ECI participants used a right CI, 13 (30.2%) used a left device, and 13 (30.2%) used bilateral devices. Fifteen (34.9%) ECI participants wore a contralateral hearing aid.

An additional 19 post-lingually deaf patients who were CICs in our clinic (using AzBio best-aided sentence testing) were also enrolled and tested. For CICs, etiologies of hearing loss were progressive loss (23.1%), noise-induced (23.1%), genetic (15.4%), trauma (15.4%), unknown (15.4%), and Meniere's disease (7.7%). Thirteen (68.4%) CIC participants wore at least one hearing aid. Mean better-ear unaided four-tone PTA at 0.5, 1, 2, and 4 kHz for CICs was 84.4 dB HL (SD 15.2).

NH control participants were recruited from patients with non-communication–related complaints, along with use of a national research recruitment database, ResearchMatch. These participants were evaluated for NH immediately prior to testing, with NH defined as a four-tone PTA obtained at 0.5, 1, 2, and 4 kHz of better than 25 dB HL in the better ear. This criterion was relaxed to a PTA of 30 dB HL for individuals over 60 years of age, but only two participalnts ended up with a PTA worse than 25 dB HL.

Participants were all native English speakers with a high school diploma or equivalency. SES was quantified based on a metric consisting of occupational and educational levels.[15] There were two scales for occupational and education levels, each ranging from 1 to 8, with 8 being the highest level. These two numerical scores were then multiplied, resulting in scores between 1 and 64. All participants were screened for vision using a basic near-vision test and were required to have better than 20/40 corrected near vision, because all of the cognitive measures were presented visually. Two ECI participants had corrected vision scores of 20/50 but displayed normal reading scores, suggesting sufficient vision to include their data in analyses. A screening task for cognitive impairment was completed, the Mini Mental State Examination (MMSE), with a raw score ≥ 26 required.[16] All participants met this criterion, suggesting no evidence of cognitive impairment. A final screening test of basic word reading was completed using the Wide Range Achievement Test (WRAT).[17] Participants were required to have a word reading standard score ≥ 75, suggesting reasonably normal general language proficiency. Lastly, participants were assessed for vocabulary knowledge and lexicon size using a self-report written word familiarity task, the WordFAM test,[18] in which participants rated low-, medium-, and high-frequency English words from 1 (have never seen the word before) to 7 (recognize word and are confident of its meaning), again serving as a proxy for general language and vocabulary knowledge.

Procedures

All procedures were completed at The Ohio State University Eye and Ear Institute. Visual stimuli were presented on paper or on a touch screen computer monitor made by KEYTEC, Inc., placed two feet in front of the participant. Several measures of cognitive functions were included and are described in detail in Appendix A. In brief, verbal working memory capacity was assessed using Visual Digit Span, Visual Object Span, and Visual Symbol Span.[19] Information-processing speed and inhibitory control were assessed using a Stroop Color-Word Interference task. Nonverbal reasoning was measured using Raven's Progressive Matrices test. Speed of phonological and lexical access were assessed using the Test of Word Reading Efficiency, version 2. Lastly, verbal learning and memory were assessed using the California Verbal Learning Test, version II.[20,21] Details regarding these tests are described in Appendix A.

General Approach

The study protocol was approved by the local Institutional Review Board at OSU. All participants provided informed, written consent, and were reimbursed $15 per hour for participation. Testing was completed within a 1-hour session, with frequent breaks. CI participants wore their typical hearing prostheses, including any contralateral hearing aid, during testing, except during the unaided audiogram. Prior to testing, examiners checked the integrity of hearing prostheses by administering a brief vowel and consonant repetition task.

Analyses

Analyses of variance (ANOVA) were performed to compare scores on demographic and non-auditory cognitive measures between ECI users, CICs, and NH participants. Where significant main effects were found, post-hoc Bonferroni analyses were completed.

RESULTS

Demographics

Group mean scores for demographic measures are shown in Table I. Results of ANOVAs demonstrated no significant group differences in participant age or reading ability. Gender frequency was not equivalent across groups; there was a significantly greater proportion of females in the NH group (65.0%) than the ECI group (41.9%) or the CIC group (31.6%). There was also a main effect of group on SES; post-hoc analyses demonstrated that this difference was driven by the NH controls who had significantly higher SES than ECI users ($P = .007$). In addition, there was a main effect of group on Vocabulary Knowledge; post-hoc analyses demonstrated that this effect was again driven by the NH controls having significantly larger vocabularies than both ECI participants ($P = .015$) and CICs ($P = .005$). There were no significant differences among groups in reported medical comorbidities including history of stroke, head trauma, brain tumor, or neurologic disorders (Parkinson's, multiple sclerosis, or amyotrophic lateral sclerosis).

Cognitive Measures

Group mean scores for the visual cognitive measures are shown in Table II. Results of ANOVAs demonstrated significant effects of group on performance on one task of WM (Symbol Span), information-processing speed (Stroop control condition), nonverbal reasoning (Raven's), speed of lexical access (TOWRE-2 words), and all three measures from the CVLT-II. For Symbol Span, post-hoc analyses revealed a trend for ECI users to perform better than NH controls ($P = .08$) and ECI users performed significantly better than CICs ($P = .002$). For Stroop, one ECI and one CIC participant demonstrated Interference Score times that were >3 SD longer than the mean, so these data were excluded from analyses. For Stroop information-processing speed, NH controls showed a trend towards being faster than ECI users ($P = .1$), and NH participants were significantly faster than CICs ($P = .011$). For Raven's, NH controls performed significantly better than ECI users ($P = .022$) and showed a trend towards better performance than CICs ($P = .088$). For speed of lexical access (TOWRE words), NH controls performed significantly better than ECI users ($P = .028$). For the CVLT-II Total Words Recalled, CICs scored significantly worse than both NH ($P = .004$) and ECI ($P = .023$) groups. For CVLT-II Short Delay Recognition, CICs again scored significantly worse than both NH ($P < .001$) and ECI ($P < .001$) groups. Finally, for CVLT-II List B performance, NH significantly outperformed ECI participants ($P = .025$) as well as CICs ($P = .004$).

A consideration in the above analyses comparing cognitive measures across groups was that SES and vocabulary size (representing general language proficiency), as well as gender, were not equivalent between

TABLE I.
Participant Demographics for Normal Hearing (NH), Experienced Cochlear Implant (ECI), and Cochlear Implant Candidate (CIC) Groups

	Groups							
	NH (*N* = 40)		ECI (*N* = 43)		CIC (*N* = 19)			
	Mean	(SD)	Mean	(SD)	Mean	(SD)	*F* value	*P* value
Demographics								
Age (years)	66.8	(6.6)	67.7	(9.3)	69.8	(9.8)	.87	.423
Reading (standard score)	101.7	(9.4)	98.0	(12.0)	96.6	(11.4)	1.85	.163
SES	35.9	(14.0)	26.1	(14.4)	28.9	(14.9)	4.96	**.009**
Vocabulary Knowledge (score)	5.29	(.80)	4.74	(.95)	4.45	(.77)	6.81	**.002**

F values and *p* values for analyses of variance (ANOVAs) are shown.
SD, Standard deviation, SES: Socioeconomic status
Results in bold are for *p*-value less than or equal to 0.05.

TABLE II.
Cognitive Scores for NH, ECI, and CIC Groups

	Groups							
	NH (*N* = 40)		ECI (*N* = 43)		CIC (*N* = 19)			
	Mean	(SD)	Mean	(SD)	Mean	(SD)	*F* value	*P* value
Cognitive measures								
Working memory capacity								
Digit span (# items correct)	48.1	(17.1)	43.2	(16.6)	38.3	(17.3)	2.27	.108
Object span (# items correct)	31.4	(10.5)	31.7	(10.5)	30.4	(13)	0.09	.918
Symbol span (# items correct)	7.8	(5.2)	11.1	(8.5)	4.6	(3.3)	6.8	**.002**
Information-processing speed and inhibitory control								
Stroop control condition (msec)	1106.8	(278.3)	1306	(475.8)	1458.3	(521.6)	4.96	**.009**
Stroop interference (msec)	325.9	(330.4)	304.5	(287.9)	435.2	(583.3)	0.78	.461
Nonverbal reasoning								
Raven's (# items correct)	13.1	(5.9)	9.9	(5)	9.8	(5.2)	4.48	**.014**
Speed of phonological and lexical access								
TOWRE non-words (% phonemes correct)	65	(15)	57.6	(17.7)	54.9	(18.2)	3.04	.052
TOWRE words (% words correct)	77.5	(9.3)	71.3	(11.8)	71.5	(10.5)	4.02	**.021**
Verbal learning and memory								
CVLT-II total words recalled (# correct)	44.7	(10.2)	42.6	(12.2)	33.5	(12.7)	5.7	**.005**
CVLT-II short delay recognition (# correct)	89.7	(7.4)	89.3	(8.3)	64.1	(33.1)	19.28	**<.001**
CVLT-II list B (% words correct)	32.5	(9.8)	25.6	(13)	21.3	(11.5)	6.71	**.002**

F values and *p* values for analyses of variance (ANOVAs) are shown.
CIC, cochlear implant candidate; ECI, experienced cochlear implant; NH, normal hearing.

groups. Thus, it could be that the differences identified above in cognitive functions among groups could be due to differences in SES, Vocabulary Knowledge, and or gender. Indeed, examining the entire group of participants together ($N = 102$), SES and Vocabulary Knowledge both correlated significantly with several of the cognitive measures, as demonstrated in Table III. Also, female participants scored significantly better on all CVLT-II measures than male counterparts. Therefore, additional analyses were carried out using univariate general linear model analysis to look for effects of group (fixed factor) on each cognitive measure after entering SES, Vocabulary Knowledge, and gender as covariates, with results shown in Table IV. For Symbol Span, the effect of group still remained significant. For Stroop information-processing speed, the effect of group still remained significant but was attenuated. For Raven's nonverbal reasoning and speed of lexical access (TOWRE words), the effect of group was no longer significant. For the CVLT-II, the effect of group was no longer significant for Total Words Recalled or List B, although it still remained highly significant for Short Delay Recognition. Thus, adding SES, Vocabulary Knowledge, and gender as covariates eliminated or attenuated the effects of group on some cognitive measures but not others.

DISCUSSION

Over the past 10 years, a great deal of attention has been given to investigating links between hearing loss and cognitive declines. If there is a causal link, then rehabilitating hearing could ameliorate associated cognitive dysfunction. When studying this relationship, it is critical to consider confounding factors, particularly SES and language knowledge. For example, lower SES has been found to be associated with hearing loss as well as decreased cognitive functions.[22,23] Also, auditory-based cognitive testing will put individuals with hearing loss at a disadvantage, and results of these tests and studies need to be scrutinized carefully.

Lin and colleagues have published extensively on the topic of hearing loss and cognitive decline. In an initial study reviewing data from the Baltimore Longitudinal Study of Aging, they examined 639 subjects and demonstrated a correlation between different levels of hearing loss (mild, moderate, and severe based on pure-tone average [PTA]) and incidence of dementia (based on consensus diagnosis and neuropsychological testing).[3] However, in that study, measures of SES and language knowledge were not reported or treated as covariates in analyses. A subsequent review of 1984 individuals aged 70 to 79 found that individuals with hearing loss (PTA > 25 dB) had a slightly higher rate of cognitive decline (as determined by the 3MS and digit substitution test), although those participants with NH also demonstrated cognitive declines.[24] Groups were not significantly different based on a relatively broad assessment of education level (ie, < 12th grade education, high school graduate, or college graduate), but no other SES or language knowledge metrics were reported.

Another large study by Gallacher and colleagues was a 17-year follow-up of about 1000 men from the United Kingdom.[4] Cognitive assessment involved an auditory interview (Cambridge Cognitive examination,

TABLE III.
Correlation *r* Values for Analyses Between SES and Cognitive Measures, as well as Between Vocabulary Knowledge and Cognitive Measures, for Entire Group of Participants ($N = 102$)

	SES		Vocabulary Knowledge	
	r value	*P* value	*r* value	*P* value
Cognitive measures				
Working memory capacity				
Digit span (# items correct)	**.23**	**.022**	.12	.229
Object span (# items correct)	−.05	.647	.08	.46
Symbol span (# items correct)	.02	.827	**.21**	**.041**
Information-processing speed and inhibitory control				
Stroop control condition (msec)	−.07	.491	−.18	.075
Stroop interference (msec)	.04	.707	−.08	.423
Nonverbal reasoning				
Raven's (# items correct)	**.19***	**.05**	**.36**	**<.001**
Speed of phonological and lexical access				
TOWRE non-words (% phonemes correct)	**.26**	**.01**	**.46**	**<.001**
TOWRE words (% words correct)	**.37**	**<.001**	**.35**	**<.001**
Verbal learning and memory				
CVLT-II total words recalled (# correct)	.08	.442	**.31**	**.002**
CVLT-II short delay recognition (# correct)	.03	.743	.13	.214
CVLT-II list B (% words correct)	.13	.215	**.3**	**.003**

SES, socioeconomic status.

MMSE, National Adult Reading Test), computer-based testing (Alice Heim part 4 and a 4-choice timed reaction), and dementia assessment as diagnosed by DSM-IV. Increased PTA was associated with incident dementia and worse auditory cognitive testing, but the association of hearing loss with results of non-auditory cognitive testing was weak. Social class (percent manual occupation) was used to approximate SES, and its inclusion in analyses was found to attenuate the association between hearing loss and poorer cognitive functions. The largest study to date linking hearing loss and cognitive decline reviewed data from 154,783 individuals over age 65

TABLE IV.
Univariate General Linear Model Analyses Comparing Cognitive Scores for NH, ECI, and CIC groups, While Controlling for Gender, SES, and Vocabulary Knowledge

	F value	*P* value
Cognitive measures		
Working memory capacity		
Digit span (# items correct)	2.04	.136
Object span (# items correct)	.09	.917
Symbol span (# items correct)	8.09	**.001**
Information-Processing Speed and Inhibitory Control		
Stroop control condition (msec)	3	**.05**
Stroop interference (msec)	.89	.413
Nonverbal Reasoning		
Raven's (# items correct)	3.01	.054
Speed of Phonological and Lexical Access		
TOWRE non-words (% phonemes correct)	.42	.657
TOWRE words (% words correct)	.66	.522
Verbal Learning and Memory		
CVLT-II total words recalled (# correct)	2.34	.102
CVLT-II short delay recognition (# correct)	17.2	**<.001**
CVLT-II list B (% words correct)	1.8	.172

F values and *P* values represent the effect of group (NH, ECI, or CIC). CIC, cochlear implant candidate; ECI, experienced cochlear implant; NH, normal hearing; SES, socioeconomic status.

years during a 6-year period.[5] An association between hearing loss and cognitive declines was found; however, SES was not reported or treated as a covariate, PTA was not reported, and specific cognitive factors were not examined. Individuals were simply categorized as having hearing loss or dementia based on ICD-10 diagnoses.

In the current study, NH peers typically outperformed ECI users on several performance-based visual cognitive tests. CIC participants performed slightly, but not significantly, worse on several measures than NH individuals, and were generally equivalent to ECI users. These findings are generally consistent with the prediction that hearing loss is associated with cognitive decline. However, we did not see large significant differences in cognitive functions between CICs and ECI users. Moreover, many of the between-groups effects obtained in our analyses of the cognitive tests were attenuated after controlling for SES, vocabulary size, and gender. These findings contradict previous research documenting the presence of a weak-to-moderate association between hearing loss and cognitive decline. In contrast, an interesting unexpected finding that deserves further exploration was that ECI participants showed trends towards better performance on the Symbol Span task of WM capacity than NH and CIC groups, possibly reflecting a shift in encoding and processing strategies used to accomplish this task by experienced CI users.[25]

There are several possible explanations for the discrepancies observed between our findings and those of previous studies. First, it is possible that the effects of hearing loss on cognition disappear (or are at least weakened) when non-auditory visual cognitive tests are administered (as demonstrated in Gallacher et al).[4] Second, after controlling for gender, SES, and vocabulary knowledge in our patients, we may have eliminated the effects of hearing loss on cognition, suggesting that the previous links demonstrated between hearing loss and cognitive dysfunction might have been mediated by differences among participants in SES and language proficiency.

This study has several limitations. First, sample sizes were relatively small, particularly for the CIC group, which may have limited our ability to identify significant group differences in cognition. Second, to more definitively identify changes in cognition attributable to CI intervention, a prospective longitudinal study is needed using CIC participants who go on to receive CIs, with repeated cognitive testing post-operatively. This longitudinal study is currently ongoing at our center. Third, this study intentionally excluded participants with evidence of any cognitive impairment. The rationale for this inclusion criterion was based on the larger goals of our ongoing study, to evaluate how cognitive functions contribute to CI speech recognition outcomes. However, by excluding participants with evidence of true documented cognitive impairment, we may have limited our ability to identify hearing loss-related cognitive changes. Finally, the battery of visual cognitive measures used in this study was not all-inclusive. The specific set of tests used in this study were chosen based on their likely relevance to speech recognition outcomes in adults who use CIs, and they may not represent all the cognitive functions that could be impacted by a significant hearing loss.

CONCLUSION

The purported link between poor hearing status and cognitive decline is not well characterized. Evidence supporting this link has largely been population-based and has not always controlled for important confounding factors like SES and general language knowledge and experience. The present study did not demonstrate large convincing discrepancies in cognitive functions between individuals with prolonged profound hearing loss and normal hearing individuals. More targeted research is needed to clarify the impact of hearing loss on cognitive decline and identify which specific cognitive functions may be affected by a significant hearing loss in elderly individuals.

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APPENDICES

Appendix A. Details of Cognitive Measures