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How Does Nonverbal Reasoning Affect Sentence Recognition in Adults with Cochlear Implants and Normal-Hearing Peers?

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Abstract

Background: Previous research has demonstrated an association of scores on a visual test of nonverbal reasoning, Raven's Progressive Matrices (RPM), with scores on open-set sentence recognition in quiet for adult cochlear implant (CI) users as well as for adults with normal hearing (NH) listening to noise-vocoded sentence materials. Moreover, in that study, CI users demonstrated poorer nonverbal reasoning when compared with NH peers. However, it remains unclear what underlying neurocognitive processes contributed to the association of nonverbal reasoning scores with sentence recognition, and to the poorer scores demonstrated by CI users.

Objectives: Three hypotheses were tested: (1) nonverbal reasoning abilities of adult CI users and normal-hearing (NH) age-matched peers would be predicted by performance on more basic neurocognitive measures of working memory capacity, information-processing speed, inhibitory control, and concentration; (2) nonverbal reasoning would mediate the effects of more basic neurocognitive functions on sentence recognition in both groups; and (3) group differences in more basic neurocognitive functions would explain the group differences previously demonstrated in nonverbal reasoning.

Method: Eighty-three participants (40 CI and 43 NH) underwent testing of sentence recognition using two sets of sentence materials: sentences produced by a single male talker (Harvard sentences) and high-variability sentences produced by multiple talkers (Perceptually Robust English Sentence Test Open-set, PRESTO). Participants also completed testing of nonverbal reasoning using a visual computerized RPM test, and additional neurocognitive assessments were collected using a visual Digit Span test and a Stroop Color-Word task. Multivariate regression analyses were performed to test our hypotheses while treating age as a covariate.

Results: In the CI group, information processing speed on the Stroop task predicted RPM performance, and RPM scores mediated the effects of information processing speed on sentence

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Author Contributions

Author A.C.M. contributed to design of the study, analysis and interpretation of data, drafting of the manuscript, final approval of the manuscript. Author J.K.M. contributed to conception of the study, revision of the manuscript for intellectual content, and final approval of the manuscript. Author I.C. contributed to design of the study, data acquisition, analysis, and interpretation, revising of the manuscript for intellectual content, and final approval of the submitted manuscript. All authors agree to be accountable for accuracy and integrity of the work.

Statement of Ethics

Participants included in this study gave their written informed consent. The Institutional Review Board of The Ohio State University approved the study protocol for human research. Animals were not included in this study.

recognition abilities for both Harvard and PRESTO sentences. In contrast, for the NH group, Stroop inhibitory control predicted RPM performance, and a trend was seen towards RPM scores mediating the effects of inhibitory control on sentence recognition, but only for PRESTO sentences. Poorer RPM performance in CI users than NH controls could be partially attributed to slower information processing speed.

Conclusions: Neurocognitive functions contributed differentially to nonverbal reasoning performance in CI users as compared with NH peers, and nonverbal reasoning appeared to partially mediate the effects of these different neurocognitive functions on sentence recognition in both groups, at least for PRESTO sentences. Slower information processing speed accounted for poorer nonverbal reasoning scores in CI users. Thus, it may be that prolonged auditory deprivation contributes to cognitive decline through slower information processing.

Keywords

Neurocognitive skills; Nonverbal reasoning; Raven's Progressive Matrices

Introduction

Cochlear implantation continues to be the most successful treatment approach for providing auditory access to individuals with severe-to-profound sensorineural hearing loss (SNHL). Variability in postoperative cochlear implant (CI) outcomes, however, continues to be an ongoing concern, and significant interest and time have been dedicated to examining the factors influencing speech recognition outcomes in both clinical and research settings. Speech recognition variability can be difficult to explain due to the numerous factors that contribute to the final endpoint outcome of speech recognition [Holden et al., 2013; Moberly et al., 2018a, b]. Known clinical contributors include duration of deafness, age at implantation, electrode position within the cochlea, as well as variables such as cognitive and linguistic skills [Aschendorff et al., 2007; Blamey et al., 1996; Collison et al., 2004; Finley et al., 2008; Heydebrand et al., 2007; Holden et al., 2013].

The primary limitation affecting speech recognition for listeners with CIs is that the signal from an implant is highly underspecified in spectral and temporal information, and the resulting acoustic-phonetic representations are degraded relative to normal speech signals [Guerit et al., 2014; Svirsky et al., 2015; Won et al., 2011]. This signal degradation requires the listener to use a variety of neurocognitive processes to interpret the signal in a meaningful way, including language knowledge and a variety of information processing skills, such as working memory (WM) capacity, information processing speed, inhibitory control, and concentration [Moberly et al., 2016a]. Information processing factors have been examined in relation to speech recognition abilities in groups of listeners with hearing loss, both in a general and modality-specific fashion, although largely in patients with milder forms of SNHL [Akeroyd, 2008; Arehart et al., 2013; Pisoni, 2000], and with a few recent explorations in CI users [Holden et al., 2013; Moberly et al., 2016b; Moberly et al., 2017; Moberly et al., 2018b]. For example, Holden et al. [2013] explored factors related to CI outcomes in adults, including cognitive abilities. Participants in that study underwent a test battery evaluating short-term memory and WM, language, executive functioning/reasoning, and verbal learning. Their results demonstrated a correlation between a composite cognitive

score and word recognition outcomes in CI users, but detailed analyses of the specific cognitive contributors were not published. More recently, Moberly et al. [2016b, 2017] examined several neurocognitive skills in CI users using visual tasks and found that inhibition-concentration and modality-specific (listening span rather than reading span) WM capacity played an important role in speech recognition abilities in CI users, but not in normal-hearing (NH) controls listening to sentences in speech-shaped noise [.

In addition to the aforementioned studies, performance on a nonauditory test of nonverbal reasoning, the visual Raven's Progressive Matrices (RPM), was recently found to correlate with sentence recognition performance in quiet in CI users, as well as in NH controls listening to 8-channel noise-vocoded speech [Mattingly et al., 2018]. The RPM is a classic nonverbal reasoning task originally developed in the 1930s as a way to assess generalized intelligence [Raven, 1938; Carpenter et al., 1990]. This test uses a series of geometric designs for which the participant must identify the missing piece of the pattern. The task focuses on "fluid intelligence," the ability of a participant to solve novel reasoning tasks involving new information, without relying on an explicit prior knowledge base [Carpenter et al., 1990]. Successful completion requires controlled attention, reasoning, abstraction, and the ability to compare [Vygotsky, 1986]. Additionally, it has a visual and nonverbal format, making it ideal for populations who exhibit difficulty processing auditory input and language, such as clinical populations with hearing loss [Carpenter et al., 1990]. In the recent study by Mattingly et al. [2018], it was predicted that fluid intelligence would be important with regard to the ability to extract a meaningful form from degraded auditory information. Indeed, scores from the RPM were found to be a moderate cognitive correlate of sentence recognition scores (r values between 0.35 and 0.57) in both CI listeners and NH participants, and performance on the RPM was also found to partially mediate the effects of advancing age on poorer speech recognition outcomes in older adult CI users [Moberly et al., 2018b]. Analyses in the Mattingly et al. [2018] study were limited to examining the relationship between RPM performance and sentence recognition abilities in CI users and NH controls listening to noise-vocoded speech. However, it is known that most tasks of fluid intelligence tap into more basic underlying neurocognitive functions, like WM capacity, information processing speed, and inhibition-concentration abilities [Carpenter et al., 1990; Dillon et al., 1981; Salthouse, 1993]. The first hypothesis (H1) tested in the current set of analyses was that more basic underlying neurocognitive functions would predict RPM performance in each group. The second hypothesis (H2) of the current study was that RPM scores would mediate the effects of these more basic underlying neurocognitive functions on sentence recognition abilities in each group of listeners.

An additional noteworthy finding from the study by Mattingly et al. [2018] was that performance on the visual RPM was significantly poorer for CI users than NH, age-matched control participants. This finding raised the question as to whether the experience of prolonged severe-to-profound SNHL might have contributed to cognitive decline in the CI users, with the link between hearing loss and cognitive decline being repeatedly demonstrated in the literature [Fritze et al., 2016; Lin et al., 2011; Thomson et al., 2017]. It is conceivable that the difference in nonverbal reasoning identified between CI users and NH controls was a consequence of hearing loss-related differences in more fundamental underlying neurocognitive functions. Thus, the third hypothesis (H3) tested in this study was

that group differences in RPM scores would be mediated by differences in more basic underlying neurocognitive functions.

Materials and Methods

Participants

Participants included 40 postlingually deafened adults with CIs and 43 NH controls, age-matched as a group to the CI users. Inclusion criteria for the CI group included being a native English speaker and being postlingually deaf. All CI users self-reported early hearing aid intervention and typical auditory-only spoken language development during childhood, inclusion in mainstream conventional education programs, and experienced progressive hearing losses into adulthood. Exclusion criteria for participation in the study included prelingual deafness, inner ear malformation on preoperative imaging (either CT or MRI), history of stroke or neurological disorder that might impact CI functioning (e.g., multiple sclerosis), or history of diagnosed cognitive impairment. All NH participants were screened for age-normal hearing, meaning they demonstrated pure-tone averages (PTA) across the speech frequencies (0.5, 1, 2, and 4 kHz) of better than 25 dB HL. This criterion was relaxed to a PTA of 35 dB HL for participants aged 65 years or older, but this only affected 5 participants who demonstrated PTAs worse than 25 dB HL.

All enrolled participants were screened for vision using a basic near-vision test and were required to have better than 20/40 near vision, because all of the cognitive measures were presented visually. Two CI participants had vision scores of 20/50; however, they still displayed reading scores in the normal range, suggesting sufficient visual abilities to include their data in analyses. A screening test for cognitive impairment was completed, using a written version of the Mini-Mental State Examination [MMSE; Folstein et al., 1975], with an MMSE raw score ≥ 26 required; all participants met this criterion, suggesting no evidence of global cognitive impairments. A final screening test of basic word reading was completed, using the Wide Range Achievement Test [WRAT; Wilkinson and Robertson, 2006], during which participants read out loud a list of words without being timed. Participants were required to have a word reading standard score ≥ 75 , serving as a proxy for general language proficiency. Socioeconomic status (SES) of participants was also collected as it may be a proxy of speech and language abilities. This was accomplished by quantifying SES using a metric developed by Nittrouer and Burton [2005]. 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. Lastly, a screening audiogram of unaided residual hearing was performed for each ear separately for all participants.

CI users were between the ages of 50 and 83 years (mean = 67.6, SD = 9.4), and were postlingually deafened. Duration of hearing loss ranged from 4 to 76 years (mean = 40.0, SD = 18.2), and the duration of CI use ranged from 18 months to 34 years (mean = 7.4, SD = 6.8). Etiology of hearing loss included progressive ($n = 18$), genetic ($n = 16$), unknown ($n = 3$), ototoxicity ($n = 1$), and Ménière's disease ($n = 1$). NH controls were between the ages of 50 and 81 years (mean = 67.4, SD = 6.9). Individual CI participant demographic data are shown in Table 1.

Equipment

All neurocognitive tests were presented on a touch screen monitor made by KEYTEC Inc., placed two feet in front of the participant. All tests were automatically scored by the computer software.

Stimuli and Stimuli-Specific Procedures

After the screening tests were completed, the measures outlined below were collected. Sentence recognition stimuli were presented over a loudspeaker at 68 dB SPL, in the clear for CI users. NH participants listened to 8-channel noise-vocoded versions of the stimuli. Scores were percentage of total full sentences repeated correctly, excluding the first two sentences of each which served as practice trials. Requiring the full sentence to be repeated correctly to be scored as correct placed higher cognitive demands on the listener than scoring percent words or key words correct.

Sentence Recognition

1. Harvard Standard Sentences – Sentences were presented via loudspeaker, and participants were asked to repeat as much of the sentence as possible. Thirty sentences from the Harvard Standard lists 1–10 were used, which were spoken and recorded by a single male talker [IEEE, 1969]. These sentences are long, complex, and semantically meaningful, consisting of an imperative or declarative structure. Examples of the Harvard Standard sentences include “A pot of tea helps to pass the evening,” and “The fish twisted and turned on the bent hook.”
2. PRESTO Sentences – These sentences were selected from the TIMIT (Texas Instruments/Massachusetts Institute of Technology) speech collection, and they balance talker gender, keywords, frequency, and familiarity, with sentences varying broadly in speaker dialect and accent [Gilbert et al., 2013]. PRESTO sentences are high-variability, complex sentences, which would be expected to be challenging. Examples of PRESTO sentences include “The cow wandered from the farmland and became lost,” and “The roof of the command post began to buckle.” Participants were asked to repeat 32 sentences.

Neurocognitive Measures

1. Nonverbal Reasoning (RPM) – This assessment was given to participants as a measure of nonverbal reasoning and fluid intelligence [Raven, 1938]. RPM presents visual displays of geometric designs in a matrix in which each design contains a missing piece, and participants must select a response box on a touch screen monitor to complete the pattern. Participants completed as many of the 48 items as possible in 10 min, and scores were total correct number of items. Participants were unaware of time constraints during testing.
2. Verbal Working Memory Capacity (Visual Digit Span) – This task assessed verbal WM capacity of the participants using visual presentation. The digit span task was based on the original auditory digit span task from the Wechsler Intelligence Scale for Children, Fourth Edition, Integrated [Wechsler, 2004]. For

this task, participants were presented with a sequence of visual stimuli in the form of digits (1 through 9) on a computer monitor. To familiarize the participants with the stimuli, one digit appeared on the screen first, followed by a screen with a 3×3 matrix of all nine numbers. Participants were asked to touch the digit on the screen that had appeared first. Next, the participants saw a sequence of numerical digits and were asked to reproduce the sequence correctly, via touching the numbers on the computer screen in the correct order, when the screen with all nine numbers appeared. The number of digits presented on each trial began with two stimuli and increased gradually as the participant continued to answer correctly, up to a maximum of seven digits. Each string of digits was presented twice (different stimuli, same string length). When the participant failed to reproduce two strings of the same length correctly, the task was automatically terminated. Digits were presented visually one at a time on a computer screen. Once the numbers disappeared from the screen, the participant was asked to touch the numbers on the screen in the correct serial order. Total correct items served as the performance score.

3. Information Processing Speed and Inhibition-Concentration (Stroop) – This computerized task, which was based on the original paper version, evaluated information-processing speed, inhibitory control, and concentration abilities and is publicly available [Stroop, 1935] (<http://www.millisecond.com>). Participants were shown a color word on the computer screen, presented in either the same or a different color font. The participant was asked to press the computer key on the keyboard that corresponded with the color of the font of the word, not the color name represented by the word. The Stroop task was divided into control trials (colored rectangle on the screen), congruent trials (font color and color word matched), and incongruent trials (font color and color word did not match). The Stroop task requires participants to actively inhibit conflicting conditions. Response times were computed for each condition, with mean response time for the control condition representing information processing speed, mean response time for the congruent condition representing concentration ability (shorter time representing better concentration), and mean response time for the incongruent condition representing inhibitory control ability (shorter time representing better inhibitory control). Across these measures, longer response times (slower responses) are reflected by larger Stroop scores.

General Procedures

All testing took place using sound-proof booths and acoustically insulated rooms for testing. All participants provided informed, written consent, and were reimbursed USD 15 per hour for participation. Testing was completed over a single 2-h session, with frequent breaks to prevent fatigue, with a subset of measures collected reported here. During testing, CI participants used their typical hearing prostheses, including any contralateral hearing aid, except during unaided audiogram testing. Prior to the start of testing, examiners checked the integrity of the individual's hearing prostheses by administering a brief vowel and consonant repetition task, and all participants passed this integrity check.

Data Analyses

First, multivariate linear regression analyses were performed separately for each group of participants (CI and NH) to determine whether more basic neurocognitive functions (WM capacity, information-processing speed, concentration, and/or inhibitory control) predicted nonverbal reasoning scores on the RPM. Next, additional regression analyses were performed for each group separately testing mediation models using the method by Baron and Kenny [1986], using each speech recognition score (Harvard or PRESTO sentences) as a separate outcome measure. To test the hypothesis that RPM scores would mediate the effects of more basic neurocognitive functions on sentence recognition, two linear regression analyses were performed, first with sentence recognition as outcome and the basic neurocognitive processes (working memory capacity, information-processing speed, concentration, and inhibitory control) as predictors, and then with sentence recognition as outcome and RPM (the potential mediator) as predictor. Third, a multiple linear regression analysis was performed to test for mediating effects. A mediation effect of RPM (the potential mediator), when RPM and the basic neurocognitive measures were entered together into the model, would be evidenced by a significant effect of RPM and a nonsignificant effect of the basic neurocognitive measures. A final set of multivariate linear regression analyses was then performed to determine whether neurocognitive functioning mediated the effects of hearing status (CI vs. NH) on RPM performance, using a similar approach as described above. For all of these regression analyses, age was included as a covariate to account for the likely relationship between advancing age and poorer cognitive function.

Results

Group Differences

CI and NH groups did not differ on age ($t(81) = 0.14$, $p = 0.89$), gender ($p = 0.13$ by Fisher's Exact Test), or reading scores ($t(81) = 1.58$, $p = 0.12$). CI and NH controls did differ on SES ($t(81) = 2.98$, $p = 0.004$), with CI users demonstrating lower SES than NH controls. As reported in Mattingly et al. [2018] and demonstrated in Table 2, two-tailed independent samples t tests demonstrated differences in RPM scores, with CI users scoring significantly more poorly compared to NH controls.

Mean sentence recognition scores for CI users on PRESTO sentences were 23.7% (SD = 20.10) full sentences correct and 41.3% (SD = 23.0) full sentences correct on Harvard sentences. For NH peers, mean PRESTO recognition scores were 19.7% (SD = 10.9) full sentences correct, and mean Harvard recognition scores were 27.8% (SD = 14.4) full sentences correct. Because CI users listened to sentences in the clear, while NH peers listened to noise-vocoded stimuli, sentence recognition scores were not directly compared between groups.

Two-tailed independent samples t test analyses were then performed to compare performance between CI and NH groups on WM capacity, information-processing speed, concentration, and inhibitory control, with results also shown in Table 2. CI users scored

significantly more poorly than NH peers on Stroop Control (information-processing speed skills) and Stroop Congruent (concentration skills).

Regression Models Predicting Functioning

To test if more basic neurocognitive abilities of WM capacity, information processing speed, concentration, and/or inhibitory control would predict RPM scores in CI users and NH peers (H1), a multivariate stepwise linear regression analysis was performed for each group (CI and NH) separately with RPM scores entered as the dependent variable, the neurocognitive variables (Digit Span, Stroop Control, Stroop Congruent, and Stroop Incongruent) entered as predictors, and age entered as a covariate. Results are shown in Tables 3 and 4. Stroop Control (information processing speed) scores and age were significant independent predictors of RPM scores in CI users, while Stroop Incongruent (inhibition) scores were a significant independent predictor of RPM scores in NH participants.

To test if RPM scores served to mediate the effects of these more basic neurocognitive processes on sentence recognition (H2), a series of linear regression analyses were performed for each group separately. In CI users, regression analyses were performed using RPM as a mediator for the effect of Stroop Control on PRESTO and Harvard sentences, whereas in NH participants, regression analyses were performed using RPM as a mediator for the effect of Stroop Incongruent on PRESTO and Harvard sentences. Age was again treated as a covariate in analyses. Results of analyses are shown in Tables 5 and 6 for CI users, and in Tables 7 and 8 for NH participants.

In CI users, the direct relation between Stroop Control and PRESTO sentences was significant, independent of any mediated effects. Consistent with our previous findings reported in Mattingly et al. [2018], the direct relation between RPM and PRESTO was also significant. The overall equation revealed that RPM mediated the effect of Stroop Control on PRESTO sentence scores, as shown in Table 5. For Harvard sentences in CI users, the direct relation between Stroop Control and Harvard sentence recognition was significant, independent of any mediated effects, and the overall equation revealed that RPM mediated the effect of Stroop Control on Harvard sentence scores, as shown in Table 6.

In NH participants, although the overall model was significant when entering Stroop Incongruent and age as predictors of PRESTO scores, $F(2,40) = 4.453$, $p = 0.018$, Stroop Incongruent did not predict PRESTO sentences independently of age, although a trend towards significance was observed ($p = 0.07$). Consistent with our previous findings reported in Mattingly et al. [2018], the direct relation between RPM and PRESTO was significant for NH participants. The overall equation revealed that RPM independently predicted PRESTO sentence scores when entered together with age and Stroop Incongruent, and the trend towards significance for Stroop Incongruent was eliminated, as shown in Table 7. Thus, a similar trend was found as for CI users, but a true mediation effect of RPM on PRESTO scores was not seen for NH controls. In contrast, as shown in Table 8, Stroop Incongruent and age did not predict Harvard sentences in NH participants, so a mediation equation was not tested.

Next, to test if neurocognitive processes served to mediate the effect of Group (CI, NH) on nonverbal reasoning skills (H3), three sets of regression equations were performed. The first equation tested for a direct relation between Group (CI vs. NH) and RPM scores. The second set of equations tested for direct relations between neurocognitive measures (Stroop Control and Stroop Incongruent) and RPM scores. Finally, the third regression equation tested the complete mediating model with simultaneous entry of Group and the neurocognitive measures as predictors of RPM scores. Again, age was entered as a covariate.

Results of these analyses are shown in Table 9. The direct relations between Group and RPM ($\beta = 0.284$, $p = 0.004$) and between Group and Stroop Control ($\beta = -0.277$, $p = 0.008$) were significant, as was the direct relation between Stroop Control and RPM ($\beta = -0.354$, $p = 0.001$). The overall equation revealed that Stroop Control partially mediated the effect of Group on RPM scores; the magnitude of the direct relation between Group and RPM ($\beta = 0.202$) was smaller with the addition of Stroop Control in the overall equation, indicating that processing speed served as a partial mediator of the effect of group on RPM performance.

Discussion/Conclusion

The link between neurocognitive performance and sentence recognition abilities in listeners with varying degrees of hearing loss, including CI users, is becoming well-accepted [Akeroyd, 2008; Arehart et al., 2013; Holden et al., 2013; Moberly et al., 2016a; Moberly et al., 2018b; Moberly et al., 2016b; Moberly et al., 2017; Pisoni, 2000]. Recent evidence has suggested that performance on a test of nonverbal reasoning, the RPM, is predictive of sentence recognition skills [Mattingly et al., 2018] in CI users, as well as NH participants listening to noise-vocoded speech. Scores on the RPM were also found to partially mediate the effects of advancing age on poorer speech recognition skills in older adult CI users [Moberly et al., 2018b]. Moreover, CI users were found to score significantly more poorly than NH, age-matched controls on the RPM. The current analyses sought to further investigate performance on RPM by assessing more basic neurocognitive functions in both CI users and NH peers, both to better understand how nonverbal reasoning contributes to the ability to recognize degraded speech, and to better elucidate the underlying neurocognitive functions that contribute to worse nonverbal reasoning in CI users as compared with NH controls.

The first major finding from this study was that differential underlying neurocognitive functions predicted nonverbal reasoning scores on RPM for our two participant groups: the Stroop Control (information-processing speed) score predicted performance on the RPM for CI users, and the Stroop Incongruent (inhibition) score predicted performance on the RPM for NH peers. This dissociation was unexpected but may suggest that the two groups of participants are using slightly different cognitive processing strategies to carry out the RPM test, or, alternatively, the RPM test places differential demands on neurocognitive resources across the two groups. We conjecture that these differences might be related to changes in information processing in CI users as a result of their prolonged auditory deprivation. It is likely that, in general, participants with NH reason through the RPM task using covert speech [Deshon et al., 1995]. In listeners with hearing loss, it is possible that the process of

accomplishing the RPM task relied less on language processing, because in this population, language is more effortful and less automatic. Nonetheless, in both groups, the significant predictor related to a measure incorporating response times. This finding is consistent with that of Salthouse [1993], who demonstrated that elderly participants' performance on the RPM appeared to be constrained by their information processing speed.

A second finding of this study was that RPM scores served to mediate the effects of these same more basic neurocognitive functions (information processing speed skills in CI users and inhibitory control skills in NH participants) on sentence recognition, for both types of sentence materials in CI users and a trend towards this effect for PRESTO in NH peers. Using multiple tests of speech, Knutson et al. [1991] also reported a moderate correlation ($r = 0.44$) between RPM and speech recognition outcomes in CI users, supporting the notion that neurocognitive skills may play a role in CI outcomes. Findings from the current study suggest that information processing speed and/or inhibitory control skills play a role in responses for the RPM and sentence recognition, but differentially between groups. In terms of the methodology, one key factor differs between the current study and that of Knutson et al. [1991] that may affect generalizability. The original version of the RPM is 40 min in length; however, in the current study, we imposed a time constraint of 10 min, which restricted participants' ability to complete all 48 test items. As Salthouse [1993] speculated, it is possible that speed of information processing influences performance on the RPM, and by imposing a time constraint, we may have effectively magnified these effects and relations.

A final major finding of this study was that CI users performed more poorly than NH peers on information processing speed (Stroop Control), and that these scores partially mediated the relationship between hearing status (CI user vs. NH control) and performance on the RPM. Thus, it may be that some of the general cognitive deficits that have previously been reported as an effect of prolonged hearing loss can more specifically be attributed to declines in information processing speed. Further studies will be required to determine whether hearing loss-related cognitive declines can be attributed more specifically to changes in information processing speed.

In conclusion, previous work has shown that a test of nonverbal reasoning, the RPM, predicts the ability to recognize degraded sentences in CI users and NH peers. In addition, CI users perform more poorly than NH peers on the RPM test. This study investigated the underlying neurocognitive functions that contribute to RPM performance and sought to identify differences in these underlying neurocognitive processes to explain poorer RPM performance by CI users. Results demonstrated that neurocognitive functions differentially contributed to RPM performance for the groups. Moreover, slower information processing speed in CI users as compared with NH peers at least partially explained their poorer performance on nonverbal reasoning. Results suggest the possibility that prolonged hearing loss in adults may contribute to slower information processing and suggest a possible avenue for targeted, individualized intervention.

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Table 1.

Participant demographics for individual cochlear implant (CI) users

Participant	Gender	Age, years	Implantation age, years	SES	Side of implant	Hearing aid	Etiology of hearing loss	Better ear PTA, dB HL
100001	F	65	54	24	Bilateral	No	Genetic/progressive as adult	120
100002	F	66	62	35	Right	Yes	Sudden, otosclerosis, progressive as adult	78.75
100004	F	67	58	12	Right	Yes	Genetic, progressive as adult	103.75
100005	F	55	44	15	Left	No	Measles	120
100006	M	70	65	30	Right	No	Genetic, progressive as adult	88.75
100007	M	60	52	36	bilateral	No	Genetic, progressive as adult, noise	105
100008	F	57	48	25	Right	Yes	Otosclerosis, progressive as adult	82.5
100010	M	79	76	48	Right	Yes	Progressive loss as an adult	70
100012	F	69	56	10.5	Bilateral	No	Progressive as adult, autoimmune	112.5
100013	M	55	50	30	Bilateral	No	Unknown	120
100019	F	76	68	30	Left	No	Progressive as adult, sudden hearing loss	108.75
100020	M	79	74	10	Left	No	Sudden hearing loss	108.75
100023	F	81	71	30	Right	No	Progressive as adult	88.75
100025	M	59	57	24	Bilateral	No	Genetic, progressive as child	120
100028	M	78	72	12.5	Bilateral	No	Progressive as child	120
100035	M	69	62	56	Bilateral	No	Progressive as adult	120
100037	F	50	35	32.5	Bilateral	No	Genetic, Meniere's	117.5
100039	F	64	61	30	Right	No	Progressive as adult, noise	103.75
100040	F	67	58	9	Bilateral	No	Progressive as adult	120
100042	M	83	76	42	Right	Yes	Progressive as adult, noise	68.75
100044	F	73	67	15	Right	No	Progressive as adult	98.75
100045	M	76	73	49	Left	Yes	Progressive as child	72.5
100048	F	79	45	15	Right	Yes	Meniere's disease	57.5
100062	M	74	72	64	Right	No	Chronic ear infections	92.5
100063	M	66	60	18	Left	No	Genetic, progressive as adult	80
100066	M	77	75	9	Bilateral	No	Unknown	105
100067	F	65	63	36	Right	No	Genetic, progressive as adult	86.25
100070	M	61	55	24	Right	No	Progressive as child	111.25

Participant	Gender	Age, years	Implantation age, years	SES	Side of implant	Hearing aid	Etiology of hearing loss	Better ear PTA, dB HL
100071	M	60	55	10.5	Left	Yes	Genetic	115
100072	F	64	59	24	Left	No	Genetic	95
100073	M	59	54	6	Right	Yes	Progressive as adult, noise	108.75
100074	M	57	55	6	Right	No	Genetic	101.25
100075	M	65	38	12	Right	No	Progressive as adult	92.5
100076	M	50	35	25	Bilateral	Yes	Progressive as adult	120
100077	M	81	80	49	Left	No	Progressive as adult	75
100078	M	70	68	42	Left	Yes	Progressive as adult	93.75
100079	M	53	36	20	Bilateral	Yes	Progressive as adult, noise	120
100081	F	74	72	35	Left	No	Progressive as adult	60
100084	M	68	65	30	Right	Yes	Meniere's disease	100
100087	M	83	82	42	Left	Yes	Genetic, progressive as adult	78

SES, socioeconomic status; PTA, pure tone average; HL, hearing level.

Table 2.

Neurocognitive scores for normal hearing and cochlear implant groups

	Groups		<i>t</i> value	<i>p</i> value
	normal hearing (<i>n</i> = 43)	cochlear implant (<i>n</i> = 40)		
<i>Nonverbal reasoning</i>				
Raven's Progressive Matrices, # items correct	13.0 (5.78)	10.1 (5.07)	2.46	0.016
<i>Working memory capacity</i>				
Digit Span, # items correct	48.4 (16.8)	43.5 (17.1)	1.32	0.190
<i>Inhibition-concentration</i>				
Stroop Control (Speed), ms	1,105.4 (272.8)	1,342.5 (515.7)	2.64	0.010
Stroop Congruent (Concentration), ms	1,135.5 (255.4)	1,371.1 (481.5)	2.81	0.006
Stroop Incongruent (Inhibition), ms	1,466.1 (492.1)	1,779.0 (950.5)	1.90	0.060

Data are presented as mean (SD).

Table 3.

Results of stepwise multivariate linear regression analysis for cochlear implant participants ($n = 40$), with Raven's Progressive Matrices (RPM) score as dependent variable and neurocognitive scores entered as predictors

Dependent measure: RPM	<i>B</i>	<i>SE(B)</i>	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ² change
<i>Model 1</i>						
Predictor:						0.429
Age (years)	-0.359	0.068	-0.655	-5.272	0.001	
<i>Model 2</i>						
Predictors:						0.100
Age (years)	-0.293	0.067	-0.536	-4.382	0.001	
Stroop Control (ms)	-0.003	0.001	-0.338	-2.768	0.009	
Excluded variables in model 2						
Digit Span (# items correct)	0.042	0.358	0.723			
Stroop Congruent (ms)	0.360	1.105	0.277			
Stroop Incongruent (ms)	0.094	0.516	0.609			

Age was entered as a covariate.

Table 4.

Results of stepwise multivariate linear regression analysis for normal-hearing participants ($n = 43$), with Raven's Progressive Matrices (RPM) score as dependent variable and neurocognitive scores entered as predictors

Dependent measure: RPM	B	SE(B)	β	t	Sig. (p)	R^2
Model 1						
Predictor:						0.123
Stroop incongruent (ms)	-0.004	0.002	-0.351	-2.400	0.021	
Excluded variables in model 1	Beta In	t	Sig. (p)			
Age (years)	-0.221	-1.469	0.150			
Digit span (# items correct)	0.106	0.704	0.485			
Stroop control (ms)	-0.108	-0.404	0.689			
Stroop congruent (ms)	-0.036	-0.152	0.880			

Age was entered as a covariate.

Table 5.

Results of multivariate linear regression analyses for cochlear implant participants ($n = 40$), testing whether Raven's Progressive Matrices (RPM) score mediated the effect of Stroop Control on PRESTO sentence recognition

Dependent measure: PRESTO Sentence Recognition	<i>B</i>	SE(<i>B</i>)	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ²
<i>Model 1</i>						
Predictors:						0.077
Age (years)	-0.146	0.353	-0.068	-0.413	0.682	
Stroop Control (Speed) (ms)	-0.013	0.006	-0.324	-1.973	0.049	
<i>Model 2</i>						
Predictors:						0.208
Age (years)	0.525	0.425	0.236	1.234	0.225	
RPM (# items correct)	2.528	0.777	0.622	3.255	0.002	
<i>Model 3</i>						
Predictors:						0.201
Age (years)	0.529	0.427	0.237	1.238	0.224	
RPM (# items correct)	2.231	0.859	0.549	2.596	0.014	
Stroop Control (Speed) (ms)	-0.005	0.007	-0.141	-0.826	0.415	

Model 1 shows the direct relation between Stroop Control and PRESTO. Model 2 shows the direct relation between RPM and PRESTO. Model 3 shows the overall equation with both RPM and Stroop Control as predictors of PRESTO sentence recognition. Age was entered as a covariate.

Table 6.

Results of multivariate linear regression analyses for cochlear implant participants ($n = 40$), testing whether Raven's Progressive Matrices (RPM) score mediated the effect of Stroop Control on Harvard sentence recognition

Dependent measure: Harvard sentence recognition	<i>B</i>	SE(<i>B</i>)	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ²
<i>Model 1</i>						
Predictors:						0.119
Age (years)	-0.166	0.394	-0.068	-0.422	0.675	
Stroop control (Speed) (ms)	-0.017	0.007	-0.377	-2.354	0.024	
<i>Model 2</i>						
Predictors:						0.181
Age (years)	0.377	0.495	0.148	0.762	0.451	
RPM (# items correct)	2.592	0.904	0.557	2.867	0.007	
<i>Model 3</i>						
Predictors:						0.196
Age (years)	0.385	0.491	0.151	0.784	0.438	
RPM (# items correct)	2.055	0.986	0.442	2.083	0.045	
Stroop control (Speed) (ms)	-0.010	0.008	-0.222	-1.300	0.202	

Model 1 shows the direct relation between Stroop Control and Harvard. Model 2 shows the direct relation between RPM and Harvard. Model 3 shows the overall equation with both RPM and Stroop Control as predictors of Harvard sentence recognition. Age was entered as a covariate.

Table 7.

Results of multivariate linear regression analyses for normal-hearing participants ($n = 43$), testing whether Raven's Progressive Matrices (RPM) score mediated the effect of Stroop Incongruent on PRESTO sentence recognition

Dependent measure: PRESTO sentence recognition	<i>B</i>	SE(<i>B</i>)	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ²
<i>Model 1</i>						
Predictors:						0.141
Age (years)	-0.399	0.238	-0.251	-1.678	0.101	
Stroop Incongruent (Inhibition) (ms)	-0.006	0.003	-0.281	-1.880	0.067	
<i>Model 2</i>						
Predictors:						0.213
Age (years)	-0.337	0.229	-0.212	-1.473	0.148	
RPM (# items correct)	0.745	0.272	0.394	2.742	0.009	
<i>Model 3</i>						
Predictors:						0.223
Age (years)	-0.279	0.232	-0.175	-1.201	0.237	
RPM (# items correct)	0.645	0.282	0.341	2.287	0.028	
Stroop Incongruent (Inhibition) (ms)	-0.004	0.003	-0.183	-1.232	0.225	

Model 1 shows the direct relation between Stroop Incongruent and PRESTO. Model 2 shows the direct relation between RPM and PRESTO. Model 3 shows the overall equation with both RPM and Stroop Incongruent as predictors of PRESTO sentence recognition. Age was entered as a covariate.

Table 8.

Results of linear regression analysis for normal-hearing participants ($n = 43$), testing for a direct relation between Stroop Incongruent and Harvard sentence recognition

Dependent measure: Harvard sentence recognition	<i>B</i>	SE(<i>B</i>)	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ²
Predictors:						ns
Age (years)	−0.502	0.327	−0.239	−1.537	0.132	
Stroop Incongruent (Inhibition) (ms)	−0.005	0.005	−0.176	−1.130	0.265	

Age was entered as a covariate.

Table 9.

Results of multivariate linear regression analyses for all participants ($n = 83$), testing whether neurocognitive functions mediated the effect of group (normal-hearing, NH, vs. cochlear implant, CI) on Raven's Progressive Matrices (RPM) scores

Dependent measure: RPM	<i>B</i>	<i>SE(B)</i>	β	<i>t</i>	Sig. (<i>p</i>)	<i>R</i> ²
<i>Model 1</i>						
Predictors:						0.266
Age (years)	-0.319	0.067	-0.454	-4.763	0.001	
Group (NH vs. CI)	3.172	1.065	0.284	2.979	0.004	
<i>Model 2</i>						
Predictors:						0.299
Age (years)	-0.239	0.069	-0.340	-3.468	0.001	
Stroop Control (Speed) (ms)	-0.005	0.001	-0.354	-3.609	0.001	
<i>Model 3</i>						
Predictors:						0.328
Age (years)	-0.255	0.068	-0.361	-3.748	0.001	
Group (NH vs. CI)	2.259	1.066	0.202	2.120	0.037	
Stroop Control (Speed) (ms)	-0.004	0.001	-0.291	-2.896	0.005	

Model 1 shows the direct relation between Group and RPM. Model 2 shows the direct relation between Group and neurocognitive measures. Model 3 shows the overall equation with both RPM and neurocognitive measures as predictors of RPM. Age was entered as a covariate.