Non-Auditory Verbal and Cognitive Skills in Cochlear Implant Users: Effects of Hearing Loss and Relations to Outcomes

Research Thesis

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Introduction

Cochlear implants (CIs) are devices that restore the sensation of hearing to patients with severe-to-profound hearing loss. These devices consist of a microphone, a signal processor, a transmitter, a receiver-stimulator, and an electrode array placed within the cochlea. The microphone receives the auditory signals, and converts the signals from acoustical to electrical energy. This energy is transmitted, via radio waves, through the patient's skin to a receiver-stimulator that sends an electrical signal to the electrode array in the cochlea. The array consists of up to 22 electrodes that electrically stimulate neural elements within specific regions of the cochlea. This modified hearing process shares features of regular hearing, except that it bypasses functions of the tympanic membrane, ossicles, and hair cells (Loizou, 1998).

The evolution of CIs over the past 40 years has resulted in large technological advancements. However, there are still many unanswered questions surrounding these devices. First and foremost, there is a great deal of variability and individual differences in outcomes among patients. This variability, in particular regarding speech recognition outcomes, continues to frustrate patients, clinicians, and researchers alike. While some CI users have speech recognition abilities comparable to normal hearing individuals, at least under quiet conditions, others can recognize less than 10% of words in quiet (Lenarz, Sonmez, Joseph, Buchner, & Lenarz, 2012). Post-lingually implanted adults, those who developed relatively normal language skills prior to losing their hearing, make up a large fraction of the population of patients with CIs, yet they remain largely understudied, and many face poor outcomes.

Factors Contributing to Variable Outcomes in CI Users

There have been several factors identified that traditionally help predict post-implantation outcomes of CI users. One of the strongest predictors of success of CI use in postlingually deafened adults is the duration of hearing loss (Blamey, Arndt, Bergeron, Bredberg, & Brimacombe, 1996; Geier, Barker, Fisher, Opie, 1999; Hamzavi, Baumgartner, Pok, Franz, & Gstottner, 2003; Oh, Kim, Kang, Lee, & Lee, 2003; Shea, Domica, & Orchik, 1990;

UK Cochlear Implant Study Group, 2004.) Previous studies have identified relationships between poorer speech recognition outcomes and a longer duration of auditory deprivation, as well as residual hearing status and preimplant hearing aid use. In the elderly population, the shorter the length of auditory deprivation, and the better the residual hearing, the better the cochlear implant outcome (Lazard, Vincent, Venail, Van de Heyning, Truy, Sterkers, Blamey, 2012; Holden, Finley, Firszt, Holden, Brenner, Potts, Gotter, Vanderhoff, Mispagel, Heyderbrand, & Skinner, 2013). Moreover, the relatively poor performance of CI users on speech recognition tasks can be attributed to the degraded auditory signal provided by the implant. One cause of this is the fact that electrode arrays physically cannot be inserted sufficiently to cover the entire cochlea. This causes a spectral mismatch between the electrode placement and the actual auditory input, which yields stimulation of cochlear regions that may not directly correspond with the given input (Guérit, Santurette, Chalupper, & Dau, 2014). In addition to frequency-to-place-mismatch of the electrodes, CIs cannot deliver highly frequency-specific information, negatively impacting the fidelity of the delivered speech signal. Even though there are usually about 20 stimulation electrodes, the actual number of effective channels is around four to seven (Friesen, Shannon, Baskent, & Wang, 2001). This is caused by the overlap of excitation that occurs due to the stimulation of groups of surviving neurons. As a result, CI users receive speech that is not only spectrally shifted due to the frequency-to-place-mismatch, but also spectrally degraded (Fu & Galvin, 2008). One method of evaluating spectral resolution is the spectral ripple discrimination task, which allows determination of spectral resolution thresholds. These thresholds have been shown to predict 25%-30% of the variability in word recognition scores for words in babble and in quiet for adult CI users (Won, Drennan, & Rubinstein, 2007). An additional factor contributing to variability in signal degradation through the CI is the electrode proximity to the modiolus. There is evidence of possible benefits of a shorter distance between the electrodes and modiolus, which houses the auditory neural elements. Specifically, a shorter distance correlates with higher speech recognition scores (Devries, Scheperle, & Bierer, 2016).

Although the degree of degradation of the sensory input ("bottom-up" processing) has been identified as a prominent factor contributing to speech recognition variability among CI users, "top-down" processing may relate to variability as well. Generally, top-down factors consist of previous linguistic skills, along with the neurocognitive functions that allow the listener to capitalize on their linguistic skills. These language factors include phonological knowledge, lexical knowledge, semantic knowledge, grammatical skills, and the ability to make use of linguistic context. Hearing impaired listeners and those with CIs, listening to signals that are degraded, must take advantage of top-down functions in order to disambiguate speech input (Stenfelt & Rönnberg, 2009).

Typically, top-down processes assume larger roles as the linguistic complexity of the speech signal increases (Benichov, Cox, Tun, & Wingfield, 2012), like the degraded auditory input provided to CI users. When a word within a sentence is recognized, it automatically triggers semantic information in long-term memory. This semantic information facilitates recognition of the entire sentence or utterance (Spehar, Goebel, & Tye-Murray, 2015). During this process, semantic and grammatical limits help with recognition by allowing listeners to apply whatever linguistic knowledge they have to interpreting the given speech signal. The listener's previous language development and experiences also permit the segmentation of the otherwise continuous speech stream into words, syllables, and phonemes (Committee on Hearing, Bioacoustics and Biomechanics, 1988).

However, CI users, depending on their duration of severe hearing loss, may have degraded linguistic representations (particularly phonological) stored in long-term memory, which may have an effect on top-down processing (Lyxell, Ronnberg, Andersson, Andersson, & Samuelsson, 1998). Due to the gradual decline in auditory input preoperatively in CI users, their phonological representations may deteriorate (Andersson, Lyxell, Ronnberg, & Spens, 2001; Schorr, Fox, van Wassenhove, & Knudsen, 2005). For example, post-lingual CI users tend to perform more poorly than normal-hearing peers on tasks that strictly involve phonological access, like nonword repetition (Moberly, Houston, & Castellanos, 2016; Moberly et al., in press). The combination in CI users of both degraded phonological representations and poorly specified sensory information being delivered by their implants, may result in difficulty with speech recognition (Lazard, Giraud, Truy, & Lee, 2011). As a result, CI users must recognize speech in a more effortful and controlled manner, and it appears that this effortful and controlled processing depends heavily on neurocognitive resources, particularly working memory (WM) (Ronnberg, Lunner, Zekveld, Sorqvist, Danielsson, Lyxell, Dahlstrom, Signoret, Stenfelt, Pichora-Fuller, & Rudner, 2013).

There is not a universally accepted definition for WM, but the definition that is commonly used in regards to speech perception is the capacity to simultaneously store and process relevant information (Daneman and Carpenter, 1980). WM, itself, can be divided into four specific processing areas: a phonological loop, a visuospatial sketchpad, a central executive, and an episodic buffer. The phonological loop is active during the processing of verbal-phonological information. The visuospatial sketchpad is specific to visual or spatial information. The central executive actively governs attention and other cognitive resources. The episodic buffer is thought to store integrated segments, or episodes in a multidimensional code, allowing for the chunking of specific sensory information (Baddeley, 2007). WM serves as a critical storage and processing mechanism for language and linguistic information processing (Baddeley, 2007).

WM capacity, the amount of information that can be stored and manipulated in an individuals' WM, has consistently demonstrated associations with speech perception abilities in adult hearing impaired listeners (Gygi & Shafiro, 2012; Kronenberger, Pisoni, Henning, Colson, & Hazzard, 2011; Pichora-Fuller & Singh, 2006; Pisoni & Clearly, 2003). Arehart and colleagues (2013) found that WM, assessed using the Reading Span Test (RST), is a primary factor of intelligibility of speech presented in noise for hearing aid users. In that study, 26 adults with sensorineural hearing loss, ages 62-92, were presented low-context sentences in quiet and in multi-talker babble at varying signal-to-noise ratios. Older listeners with both greater degrees of hearing loss and lower WM function demonstrated worse performance when listening through their hearing aids (Arehart et al., 2013). It is likely that older CI users would demonstrate similar effects of WM, considering they too experience highly degraded auditory signals through their devices.

Several studies have shown that pre-operative verbal WM abilities predict post-operative speech recognition in children (Harris, Pisoni, Kronenberger, Gao, Caffrey, & Miyamoto, 2011; Harris, Kronenberger, Gao, Hoen, Miyamoto, & Pisoni, 2013). The same degree of research attention has not been paid to the neurocognitive functions of post-lingually deaf adults who receive CIs, with the exception of two recent studies (Moberly, Houston, & Castellanos, 2016; Moberly et al., 2016). Although WM capacity did not correlate with speech recognition outcomes in adult CI users in either study, in the Moberly, Houston, & Castellanos (2016) study, a significant correlation was identified between sentence recognition in speech-shaped noise and inhibition-concentration skills, assessed using a computerized version of a Stroop task. Findings from that study support a role in sentence recognition of inhibition-concentration abilities, which may contribute to the ability to ignore non-target stimuli and inhibit the activation of incorrect lexical units (Moberly, Houston, & Castellanos, 2016).

Effects of Hearing Loss on Top-Down Functions

The above findings suggest that neurocognitive functions contribute to speech recognition abilities for patients with hearing loss; conversely, there is increasing evidence that hearing loss itself may contribute to short- or long-term changes in neurocognitive functioning. As a result of absolute auditory deprivation, or relative auditory deprivation when listening to a degraded speech signal through a CI or hearing aid, more intentional and effortful processing is required during the beginning stages of speech perception. This effortful processing, in turn, can shift cognitive resources to aid in the perceptual processing of the sensory input, resulting in fewer cognitive resources dedicated to higher-level processing of speech, such as encoding the speech for recall, or using that information for more complex comprehension tasks (Wingfield, Tun, & McCoy, 2005). This idea is the basis for the “effortfulness” hypothesis established over

30 years ago (Rabbitt, 1968), and this shift in cognitive resources in listeners with hearing loss may result in apparent declines in unrelated cognitive functions. For example, Lin and colleagues (2011) found that poorer hearing ability in older adults was associated with both lower memory test scores through the use of a Free and Cued Selective Reminding Test, which measures memory through immediate recall of items using a cue card that fits a specific semantic category, followed by free recall of these same items. Poorer hearing in older adults was also associated with lower executive function), including functions like attention and inhibition. Wingfield, Tun, and McCoy (2005) reported that individuals with mild-to-moderate hearing loss demonstrated poorer performance than normal-hearing peers on word-list recall tasks. The words were presented in an auditory manner, in 15-word increments. This observed discrepancy between individuals' scores with normal-hearing and those with mild-to-moderate hearing loss could be a consequence of effortful listening, utilizing cognitive resources that would otherwise be allocated to additional processing after the initial speech perception process was completed.

Additional studies evaluating the relationship between hearing loss and cognitive function of adults over 60 years of age show that, relative to normal-hearing peers, adults with hearing loss demonstrate decreased cognitive function, accelerated declines in cognition, and an increased risk of dementia (Gussekloo, de Craen, Oduber et al., 2005; Lin, 2011; Lin, Ferrucci., Metter, An, Zonderman, & Resnick, 2011; Lindenberger & Baltes, 1994). Not only is the presence of hearing loss associated with declines in cognition but also the degree of the hearing loss. More severe hearing loss has been associated with greater cognitive dysfunction (Uhlmann, Karson, Rees, & Koepsell, 1989). However, none of the above studies examined cognitive functions in adults with severe-to-profound hearing loss, nor did they examine patients who use CIs.

To our knowledge, only a small number of studies have compared cognitive functions in postlingually deafened adult CI users to normal-hearing age-matched peers, and results are mixed. In addition to examining the contributions of neurocognitive functions to speech recognition in adult CI users, the study by Moberly, Houston, and Castellanos (2016) compared cognitive functions of 30 CI users with those of 30 age-matched normal-hearing peers, using nonauditory measures of WM, controlled fluency, and inhibition-concentration. Scores were similar across groups for most tasks, except for significantly poorer scores by the CI users on a task of forward WM. In another recent study by Moberly et al. (2016), CI users and normal-hearing controls were tested using auditory tasks of digit span and serial recall of monosyllabic words. Scores for digit span (forward and backward) were similar, but CI users scored slightly poorer on the serial recall task. Thus, there is only weak evidence in adult CI users that their experience of severe-to-profound hearing loss was associated with cognitive declines. However, it should be noted that the participants in those studies were experienced CI users, and one report by Mosnier et al. (2015) has suggested that the majority of their adult CI users demonstrated improvements in cognitive functions after receiving and using their CIs for 12 months. Although not conclusive, their findings suggest that CIs and possibly hearing aids might play a role as cognitive rehabilitative devices, leading to improved cognition for postlingually deafened adults. Also, Taljaard and colleagues (2015) examined data from 602 adult participants with untreated hearing loss, 672 participants with treated hearing impairment, 176 healthy controls, and 4260 individuals with a range of hearing impairment with or without treatment. Using a battery of cognitive tests to assess attention, processing speed, word knowledge, short-term memory and WM, long-term memory, and executive functioning, the authors found that those with normal hearing demonstrated better cognitive functions compared to those with hearing loss (treated or untreated). Lin published similar results examining a small cohort of his participants who reported hearing aid use (Lin, 2011). The use of hearing aids was significantly associated with higher cognitive scores on the Digit Symbol Substitution Test, a subtest of the Wechsler Adult Intelligence Test).

Current Study

The current study examined the effects of prolonged auditory deprivation on non-auditory verbal and cognitive skills by postlingually deafened adult CI users, compared with normal-hearing (NH) adults, and related these skills to speech recognition abilities. The previously demonstrated correlations between speech recognition and cognitive abilities in adult listeners with hearing loss and/or hearing aids serve as a basis for our first hypothesis that top-down cognitive abilities would predict speech recognition under degraded conditions. These degraded listening conditions were a result of either use of a CI (our experienced CI-user group) or by spectrally degraded noise-vocoded speech (our normal-hearing control group). Particular top-down skills that were evaluated for their associations with speech recognition included measures of WM, rapid lexical and phonological access, inhibition-concentration, perceptual closure, nonverbal reasoning, and vocabulary/word familiarity.

The second hypothesis tested was that the experience of severe-to-profound hearing loss would be associated with poorer cognitive abilities, as demonstrated by poorer scores on these cognitive tasks by CI users relative to age-matched normal-hearing controls. This hypothesis was based on the findings from multiple studies that hearing loss is independently associated with declines in cognitive functioning, and that these declines are proportionally related to the degree of hearing loss (Lin et al., 2011; Tay, Wang, Kifley, & Lindely, 2006; Uhlman, et al., 1989; Gussekloo, et al., 2005). Thus, this research study examined whether hearing loss was associated with declines in cognitive skills in a clinical population of patients with more severe hearing loss, namely adults with CIs.

Methods

Participants

The study sample was comprised of twenty-six adult CI users and twenty age-matched normal-hearing (NH) controls. Participants were all native English speakers, over 25 years of age, who had a high school diploma or equivalency. All participants were screened for vision using a basic near-vision test, for cognitive impairment using the Mini Mental State Examination (MMSE; Folstein & Folstein, 1975), and for basic word reading using the Wide Range Achievement Test (WRAT; Wilkinson & Robertson, 2006). Participants were required to have better than 20/30 near vision, MMSE T scores >29 (suggesting no evidence of cognitive impairment), and a word reading standard score > 85. CI users were post-lingually deafened, meaning they should have developed reasonably proficient language skills prior to losing their hearing. Thus, CI candidates included in the study were required to have onset of hearing loss no earlier than age 12 years. Prior to implantation, all CI users had met candidacy requirements for cochlear implantation, including severe-to-profound hearing loss in both ears. The CI participants were enrolled from the patient population of the Otolaryngology department at OSU. Age-matched NH participants were recruited from a pool of research participants from previous studies and from ResearchMatch, a national recruitment database currently in use at OSU. These participants' normal-hearing ability was based on recent audiograms, validating their ability to detect those frequencies necessary for speech intelligibility. Socioeconomic status of our participants was also collected because it may be a contributor to vocabulary and language abilities (Moberly, Houston & Castellanos, 2016). This was done by quantifying SES based on a metric developed by Nittrouer and Burton, consisting of occupational and educational levels (Nittrouer & Burton, 2005). There were two scales for education level and occupation, each ranging from 1-8, with eight being the highest level. The numerical scores were multiplied, resulting in scores between 1 and 64. Details of individual CI participants can be found in Table 1.

Equipment and Materials

All testing for this study took place at Ohio State's Eye and Ear Institute, providing a central testing location for subjects across the central Ohio area. The Eye and Ear Institute is equipped with sound-proof booths and acoustically insulated rooms for testing. Visual stimuli were presented on paper or on a touch screen monitor, placed two feet in front of the participant. Auditory stimuli were presented via speaker positioned one meter from the listener at zero-degrees Azimuth. All tests with auditory responses were audio-visually recorded for later scoring. Participants wore FM transmitters through the use of specially designed vests. This allowed for their responses to have direct input into the camera, permitting later scoring of tasks. Each task was scored by two separate individuals to ensure reliable results.

Subjects were tested over a single 2-hour session. During testing, CI participants used their typical hearing prostheses, including any contralateral hearing aid, except during the unaided audiogram. Prior to the start of testing, testers checked the integrity of the individual's hearing prostheses by administering a brief vowel and consonant repetition task.

Speech Recognition Measures

Speech recognition tasks were presented in quiet and unprocessed for CI users. For NH peers, 8-channel noise-vocoded versions of speech materials were presented. Several speech recognition measures were included:

1. Harvard Standard Sentences- Sentences were presented via loudspeaker, and participants were asked to repeat as much of the sentence as they could. The sentences were semantically and grammatically correct. Scores were percentage of total words repeated correctly.
2. Harvard Anomalous Sentences - Participants were asked to repeat sentences, but these sentences did not make sense semantically. However, they retained correct syntactic structure. Scores were percentage of total words repeated correctly.
3. PRESTO Sentences – Participants were again asked to repeat sentences, but these sentences vary broadly in speaker dialect and accent. Scores were again percentage of total words correct.
4. CID-W22 wordlists- During this word recognition task, participants were prompted by a male speaker to repeat presented words embedded in the carrier phrase, "Say the word --." Scores were percentage of whole words correct.

Linguistic and Cognitive Measures

1. Test of Word Reading Efficiency (TOWRE) - TOWRE is a phonemic decoding efficiency task, which assesses the speed of the participant's lexical and phonological access (Torgesen, Wagner, & Rashotte, 1999). Participants read as many words as possible out of a list of 108

words within 45 seconds, followed by 66 nonwords within a second set over 45 seconds. Two scores were computed: percent whole words correct and percent whole nonwords correct.

2. WordFam - WordFam is a word familiarity test that presents words across three levels of word frequencies – high, medium, and low – and asks the subject to categorize them by using a number scale (1=never seen or heard the word before, through 7= extremely familiar with the word) (Pisoni, 2007). Scores demonstrate vocabulary and word familiarity of high, medium, and low frequency words. WordFam scores consist of the mean scale score for each word category of high, medium, and low frequency words.

3. Visual Digit Span - Digits were presented visually one at a time on a computer screen. Span length started at two and gradually increased in length up to seven digits. Once the numbers disappeared from the screen, the participant was asked to press the numbers on a touchscreen monitor in the correct serial order that they appeared on the screen. Total correct items served as the performance score.

4. Visual Object Span - This task was completed in the same fashion as Digit Span, except that stimuli pictures of common objects that were displayed on the computer screen, including a comb, thumb, leaf, lamp, shirt, kite, fish, nail, and bag. Performance of this task likely relies on phonemic encoding of the words representing these objects. Participants were presented with a series of two to seven pictures on the computer screen, and were asked to touch the objects in the same serial order.

5. Visual Symbol Span – This task was similar to Object Span, but the visual stimuli were symbols that did not correspond directly to objects. This task was included to examine participants' ability to repeat in correct serial order visual items that would be difficult to encode phonemically, because these symbols do not have easily associated names.

6. Fragmented Sentences Test – This task measures participants' perceptual closure ability. Single whole sentences consisting of visually fragmented words appeared for 2 seconds on a computer screen. Participants were asked to read aloud as much of each sentence as possible during and for 2 seconds after the sentence was displayed on the screen. This task was used to

assess linguistic closure ability. Studies using similar tasks have found correlations between these abilities and speech perception in noise for normal hearing individuals (Zekveld, Kramer, & Festen, 2011; Zekveld, Rudner, Jonhsrude, Dirk, Heslenfield, & Ronnberg, 2012). Fragmented Sentences was scored with both percentage of words correct as well as percentage of whole sentences correct.

7. Ravens Matrices - This is a task of nonverbal reasoning and cognition. Patterns were presented on a touchscreen and participants completed the pattern by selecting the option that best fit the pattern. Participants completed as many items as possible in 10 minutes, and scores were total correct number of items.

8. Stroop – This computerized task evaluated inhibition-concentration ability. Participants were shown a color word on the computer, presented in either the same or a different color. The participant was asked to press the computer key on the keyboard that corresponded with the color of the text of the word, not the color represented by the word. The Stroop task was broken into congruent (color and color word matched) and incongruent (color and color word did not match) trials. Response times were computed for each condition, and an interference score was calculated by subtracting the response time for congruent from the response time for incongruent condition.

Results

Independent-samples *t*-test results comparing CI users and normal hearing controls revealed no significant difference in mean age between CI users and controls, although CI users had a wider age range. CI users demonstrated socioeconomic status scores that were lower than NH peers. Groups demonstrated equivalent scores for WRAT word reading and the MMSE, as demonstrated in Table 2.

To address our primary question of the effects of non-auditory linguistic and cognitive skills on speech recognition ability under degraded conditions, correlational analyses were performed for each group separately (CI and NH) between scores of tasks of word and sentence recognition and scores on the cognitive/language measures. For CI users, a number of correlations were found, with results shown in Table 3. The response times for the Stroop congruent condition (assessing concentration) correlated with Harvard Standard Sentences and Presto Sentence scores. The response times for the Stroop incongruent condition (assessing inhibitory control speed) also correlated with Presto scores, CID scores, and Harvard Standard Sentences scores. The Stroop interference scores correlated with CID word recognition and Harvard Standard Sentence recognition. Scores for Fragmented Sentences demonstrated a correlation with Presto Sentences. Real word scores of the TOWRE task correlated with all speech recognition measures. For the nonword portion of TOWRE, CI users' scores correlated with all sentence scores. Ravens scores correlated with all speech recognition scores. There were no significant correlations between WordFam scores and speech recognition for CI users. Because several correlations were performed using measures assessing 6 linguistic/cognitive skills (WM, concentration-inhibition, perceptual closure, rapid verbal processing, and vocabulary/word familiarity), a Bonferroni correction was applied to account for family-wise error ($p = .05/6 = .008$). Using this more stringent criterion, several of these correlations remained significant, particularly for the Ravens, TOWRE, and Stroop tasks.

For NH participants, a few significant correlations were identified between linguistic/cognitive scores and speech recognition scores, as shown in Table 4. For the Stroop task, there were relationships between response times on the congruent and incongruent conditions and PRESTO Sentences. Response times for the congruent condition also correlated with Harvard Standard Sentences. Fragmented sentence scores correlated with CID word recognition scores, Harvard Standard Sentence scores, and Presto Sentence scores. TOWRE real word scores correlated with Presto Sentences. TOWRE nonword scores correlated with both Harvard Standard and Presto Sentences. Ravens scores for NH participants showed correlations with all speech recognition scores. WordFam (all three lists) were correlated with Harvard Standard Sentence scores. After again applying a Bonferroni correction ($p = .05/6 = .008$), most of these correlations were no longer significant for the NH group.

Our second hypothesis was that the experience of severe-to-profound hearing loss would be associated with poorer cognitive abilities in CI users relative to age-matched normal-hearing controls. To test this hypothesis, independent-samples *t*-tests were performed to compare cognitive scores between CI and NH groups, with results shown in Table 2. As previously stated, CI users and NH participants demonstrated equivalent scores for both the WRAT word reading and the MMSE. Stroop congruent trial response times were longer for CI users than for the NH controls. CI users also had lower scores on WordFam, indicating smaller vocabularies for middle- and high- frequency words. Conversely, CI users had better performance on visual symbol span compared to NH participants.

Discussion

This study addressed two main hypotheses. First, we predicted that top-down cognitive abilities would correlate with speech recognition skills under spectrally degraded listening conditions. The second hypothesis was that the experience of severe-to-profound hearing loss would be associated with poorer cognitive abilities, as evidenced by poorer cognitive test scores by CI users relative to age-matched NH controls. There is some support for both hypotheses in the literature, but mainly for individuals with lesser degrees of hearing loss (Lin et al., 2011; Tay, et al., 2006; Uhlman, et al., 1989; Gussekloo, et al., 2005; Taljaard, Olaithe, Brennan-Jones, Eikelboom, & Bucks, 2015).

Findings from the Stroop task of inhibition-concentration provided some support for our first hypothesis. Participants' response times for the congruent condition (the "concentration" condition) correlated negatively with scores of sentence recognition (Harvard Standard Sentences and PRESTO Sentences) for both the CI and NH groups. Because the color and color-word match during the congruent condition, it is test of basic processing ability and speed under concentration demands. Our findings suggest that concentration abilities play relatively similar roles in sentence recognition between the two groups. However, the finding that response times for the incongruent Stroop condition correlated with sentence recognition primarily for CI users, but not NH controls, suggests that inhibitory control may contribute differentially to sentence recognition outcomes in that population than in NH peers.

Similar findings using the Stroop task were reported by Moberly, Houston, and Castellanos (2016). In that study, correlations were found between response times for the Stroop incongruent condition and sentence recognition tasks in speech-shaped noise for CI users. However, that study did not find any relationships between response times for the Stroop congruent condition and sentence recognition tasks in CI users, nor any relationships of response times on the Stroop task with speech recognition for NH controls. Although not completely consistent with the findings here, our findings suggest that inhibitory control is a contributor to CI users' sentence recognition abilities. The finding of correlations between our NH group's Stroop response times and their sentence recognition scores in this study might be attributable to the fact that noise-vocoded stimuli were used to assess degraded speech recognition in this study, whereas testing was done in speech-shaped noise in the Moberly, Houston, & Castellanos (2016) study.

Findings from the TOWRE task demonstrated relationships with the sentence recognition scores for both groups. It has previously been shown that post-lingually deafened adults perform significantly poorer than their NH counterparts in cognitive tasks that require explicit phonological access (Lyxell, Ronnberg, & Samuelsson, 1994; Lyxell, Andersson, Arlinger, Bredberg, Harder, & Ronnberg, 1996), likely as a result of the degradation of phonological representations that CI users have stored in long-term memory (Lyxell et al., 1998). Because the TOWRE task is a timed task, it may be tapping into participants' abilities to rapidly access lexical and phonological information in long-term memory, even when words or nonwords are presented in a visual fashion. For both groups (CI and NH), more rapid access to lexical and phonological information may help some listeners recognize degraded sensory input, either through their implants or when listening to vocoded speech.

The Fragmented Sentences task scores also showed relationships with sentences recognition tasks in both the CI and NH groups. Overall, CI users' scores correlated with fewer speech recognition tasks (PRESTO) compared to the NH group (CID wordlists and Harvard Standard Sentences). The Fragmented Sentences task assesses participants ability to perform perceptual closure (or perceptual organization) on a visually presented distorted sensory signal. Scores on a similar task, the Text Reception Threshold task, were found to correlate with speech in noise (Besser, Zekveld, Kramer, Ronnberg, & Feston, 2012). The ability to understand speech in noise could be related to speech perception for CI users, since they experience a degraded auditory signal.

Our second hypothesis, that the experience of severe-to-profound hearing loss would be associated with poorer cognitive abilities, was not supported by our findings. Although we did find some trends towards poorer cognitive performance in our CI users compared with their NH peers, differences were not significant. Overall, CI users demonstrated longer response times on both Stroop conditions, suggesting slower processing speeds. CI users also demonstrated lower scores on the WordFam task, suggesting smaller vocabulary size. A possible contributor to this difference in vocabulary size was CI users' lower SES. Scores on the Ravens task of nonverbal reasoning also showed a trend towards CI users performing more poorly than the NH group. It should be noted that during our Ravens task we enforced a time restriction of ten minutes to complete as many items as possible, which is not standard protocol. As a result of the time limit, we might have been measuring an element of processing speed in addition to nonverbal reasoning and IQ. The identified relationship between Ravens scores and speech recognition skills could be attributable to the rapid processing required to understand running speech. Lastly, an unexpected finding was that CI users performed better on the symbol span task than NH peers. This finding might suggest that CI patients utilize an alternative processing strategy (i.e., more visually based) to aid in memory during some tasks, and this topic deserves further exploration.

This study has some limitations that should be considered in interpreting the findings. First, our CI group had a broader age range than our NH group. This could have led to a more restricted range of performance on cognitive and speech recognition measures in the NH controls, relative to CI users, limiting our ability to detect statistically significant correlations. Additionally, many of the CI users who participated in our study tend to actively participate in multiple research opportunities and strive to perform optimally with their implants. This may have led to enrollment of CI participants who performed on the upper end of the spectrum of cognitive performance, which would make it less likely for us to demonstrate any cognitive deficits that might be attributable to hearing loss.

Conclusion

To investigate the effects of hearing loss on linguistic and cognitive functions, and the variability of CI speech recognition outcomes, we studied these factors in adult CI users and age-matched NH counterparts. Most cognitive functions were similar between groups. Surprisingly, CI users demonstrated better performance on the working memory task of visual symbol span. This might be due to an alternative memorization strategy utilized by CI users. Better word and sentence recognition scores were associated with better scores of inhibition-concentration, nonverbal reasoning, rapid reading, and perceptual closure. Findings from this study will lay the groundwork for the development of a more comprehensive understanding of how verbal and cognitive factors influence outcomes for individuals with CIs.

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Table 1. Cochlear implant participant demographics

Participant	Gender	Age (years)	Implantation Age (years)	Wear HA currently	SES	Duration of Deafness (years)	Side of Implant	Etiology of Hearing Loss	Better ear PTA (dB HL)	Harvard Standard Sentences (all words % correct)
100001	F	65	54	No	24	24	Bilateral	Genetic or inherited	120.0	89.83
100002	F	66	62	Yes	35	32	Right	Genetic/inherited, progressive loss as an adult	78.8	86.86
100004	F	67	58	Yes	12	42	Right	Genetic/Progessive as an adult	103.8	88.14
100006	M	70	65	No	30	53	Right	Genetic or inherited, Progressive loss as an adult	88.8	80.08
100008	F	57	48	Yes	25	50	Right	Genetic, progressive loss as a child/an adult	82.5	83.05
100010	M	79	76	Yes	48	19	Right	Genetic/inherited, progressive as an adult	70.0	74.58
100012	F	69	56	No	10.5	54	Bilateral	Otosclerosis, progressive as adult	112.5	78.39
100013	M	55	50	No	30	34	Bilateral	Progrssive loss as an adult	120.0	88.56
100019	F	76	68	No	30	31	Left	Progressive loss as an adult, probable autoimmune cause	108.8	62.29
100020	M	79	74	No	10	76	Left	Unsure - Infection or Fever	108.8	61.44
100023	F	81	71	No	30	19	Right	Progressive as an adult, sudden hearing loss	88.8	80.93
100025	M	59	57	No	24	4	Bilateral	Sudden hearing loss due to unknown causes	120.0	85.17
100028	M	78	72	No	12.5	21	Bilateral	Progressive loss as an adult	120.0	78.81
100035	M	69	62	No	56	55	Bilateral	Genetic/inherited, progressive loss as a child	120.0	76.69
100037	F	50	35	No	32.5	50	Bilateral	Progressive loss as a child	117.5	86.86
100039	F	64	61	No	30	10	Right	Progressive loss as an adult	103.8	86.86
100040	F	67	58	No	9	31	Bilateral	Genetic	120.0	86.86
100042	M	83	76	Yes	42	33	Right	Progressive loss as an adult, noise exposure	68.8	66.95
100044	F	73	67	No	15	72	Right	Progressive loss as a child	98.8	78.39
100045	M	76	73	Yes	49	16	Left	Progessive loss as an adult	72.5	45.34
100048	F	79	45	Yes	15	49	Right	Progressive loss as an adult	57.5	52.97
100062	M	74	72	Yes	64	74	Right	Born with hearing loss	92.5	69.07
100063	M	66	60	No	18	52	Left	Meniere's disease	80.0	90.68
100067	F	65	63	No	36	59	Right	Genetic or Inherited, Progressive as an adult	86.3	77.54
100068	F	62	59	No	14	4	Bilateral	Sepsis, ototoxic meds	95.0	
	Mean	69.16	61.68		28.06	38.56			97.4	77.3475
	S.D.	8.644266	10.2782943		15.04529	21.09716			19.36129	12.0493793

Table 2. Participant demographics and test scores

	Groups					
	NH (*N* =37)		**CI (*N* = 26)**			
	Mean	(SD)	Mean	(SD)	*t* value	*p* value
Demographics						
Age (years)	68.7	5.8	69.2	8.6	0.16	0.87
MMSE (*T* score)	56.5	11.2	52.8	11.4	-1.26	0.21
Word reading (Standard score)	102.2	10.2	101.5	11.5	-.25	0.80
Verbal and Cognitive Scores						
Stroop congruent response time (msec)	1137.8	252.9	1434.6	558.3	2.81	**0.007**
Stroop incongruent response time (msec)	1496.4	516.4	1859.6	1156.6	1.67	0.101
Stroop interference score (msec)	358.5	354.2	425.1	741	0.47	0.64
Visual digit span (points correct)	48.3	17.9	42.9	17.9	-1.17	0.25
Visual object span (points correct)	30.3	10.2	33.9	7.5	1.50	0.14
Visual symbol span (points correct)	7.3	4.7	13.4	9.8	3.25	**0.002**
TOWRE nonwords (% correct)	67.1	16.9	64.5	15.2	-0.59	0.55
TOWRE words (% correct)	77.2	9.9	73.3	9.1	-1.56	0.12
Fragmented sentences (% words correct)	72.8	8.7	69.8	10.5	-1.23	0.22
Fragmented sentences (% sentences correct)	45.3	12.8	39.5	14.9	-1.66	0.11
Ravens (number correct)	12.4	5.6	9.7	5.7	-1.82	0.07
WordFam low-frequency (familiarity score)	3.9	1.2	3.2	1.2	-2.08	**0.04**
WordFam high-frequency (familiarity score)	6.7	0.2	6.7	0.4	-1.47	0.15
WordFam mid-frequency (familiarity score)	5.3	0.9	4.8	1.1	-1.95	0.06
Speech Recognition						
Harvard Standard Sentences (percent words correct)	64.2	12.7	77.3	12.1		
CID Isolated Words (percent words correct)	42.7	11.4	74.3	21.2		

Table 3. Correlations of sentence/word recognition scores with cognitive scores for CI users.

Cognitive tasks		Stroop response time congruent (msec)	Stroop response time incongruent (msec)	Stroop score interference (msec)	Fragmented Sentences (words)	Fragmented Sentences (sentence)	TOWRE words (% correct)	TOWRE nonwords (% correct)	Ravens (number correct)	WordFam low-frequency (familiarity score)	WordFam mid-frequency (familiarity score)	WordFam high-frequency (familiarity score)	Visual Digit Span (points correct)	Visual Object Span (points correct)	Visual Symbol Span (points correct)
Speech tasks															
CID (% words correct)	Pearson Correlation	-0.336	-0.441	-0.462	0.277	0.519	0.519	0.354	**0.617**	-0.019	0.075	0.313	0.158	0.131	0.347
	p value	0.117	0.035	0.027	0.2	0.036	0.011	0.097	**0.002**	0.93	0.733	0.146	0.47	0.551	0.105
Harvard Standard Sentences (% words correct)	Pearson Correlation	**-0.581**	**-0.597**	**-0.526**	0.384	**0.541**	**0.631**	**0.693**	**0.717**	0.235	0.334	0.388	0.141	0.101	0.337
	p value	**0.003**	**0.002**	**0.008**	0.064	**0.006**	**0.001**	**<0.001**	**<0.001**	0.27	0.111	0.061	0.511	0.639	0.107
Harvard Anomolous (% words correct)	Pearson Correlation	-0.337	-0.264	-0.171	0.277	0.449	**0.577**	0.407	**0.758**	0.018	0.089	0.079	-0.007	0.068	0.204
	p value	0.108	0.213	0.425	0.189	0.028	**0.003**	0.048	**<0.001**	0.932	0.68	0.713	0.974	0.752	0.339
PRESTO (% words correct)	Pearson Correlation	**-0.556**	-0.477	-0.349	0.476	**0.543**	0.456	0.508	**0.685**	0.256	0.305	0.232	0.033	0.062	0.289
	p value	**0.005**	0.018	0.094	0.019	**0.006**	0.025	0.011	**<0.001**	0.228	0.147	0.275	0.877	0.772	0.171

Table 4. Correlations of sentence/word recognition scores with cognitive scores for normal-hearing participants.

Cognitive tasks		Stroop response time congruent (msec)	Stroop response time incongruent (msec)	Stroop score interference (msec)	Fragmented Sentences (words)	Fragmented Sentences (sentence)	TOWRE words (% correct)	TOWRE nonwords (% correct)	Ravens (number correct)	WordFam low-frequency (familiarity score)	WordFam mid-frequency (familiarity score)	WordFam high-frequency (familiarity score)	Visual Digit Span (points correct)	Visual Object Span (points correct)	Visual Symbol Span (points correct)
Speech tasks															
CID (% words correct)	Pearson Correlation	-0.263	-0.332	-0.31	0.386	0.395	0.162	0.206	0.406	0.085	0.077	0.091	0.066	0.142	-0.026
	p value	0.177	0.084	0.108	0.043	0.037	0.41	0.292	0.032	0.669	0.696	0.644	0.739	0.472	0.895
Harvard Standard Sentences (% words correct)	Pearson Correlation	-0.345	-0.311	-0.211	0.395	**0.519**	0.203	0.4	**0.579**	0.314	0.243	0.205	0.338	0.254	0.323
	p value	0.05	0.078	0.239	0.023	**0.002**	0.257	0.021	**<0.001**	0.086	0.187	0.27	0.054	0.154	0.066
Harvard Anomolous (% words correct)	Pearson Correlation	-0.213	-0.157	-0.078	0.216	0.219	0.256	0.192	0.41	0.396	0.435	0.416	0.183	0.276	0.078
	p value	0.233	0.384	0.664	0.228	0.221	0.15	0.285	0.018	0.027	0.014	0.02	0.309	0.12	0.668
PRESTO (% words correct)	Pearson Correlation	**-0.485**	-0.401	-0.349	0.297	0.396	0.387	0.331	0.365	0.279	0.162	0.077	0.31	-0.031	0.3
	p value	**0.004**	0.021	-0.242	0.093	0.022	0.026	0.06	0.037	0.128	0.384	0.679	0.079	0.863	0.089