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Preoperative Reading Efficiency as a Predictor of Adult Cochlear Implant Outcomes

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Hypotheses: 1) Scores of reading efficiency (the Test of Word Reading Efficiency, second edition) obtained in adults before cochlear implant surgery will be predictive of speech recognition outcomes 6 months after surgery; and 2) Cochlear implantation will lead to improvements in language processing as measured through reading efficiency from preimplantation to postimplantation.

Background: Adult cochlear implant (CI) users display remarkable variability in speech recognition outcomes. “Top-down” processing—the use of cognitive resources to make sense of degraded speech—contributes to speech recognition abilities in CI users. One area that has received little attention is the efficiency of lexical and phonological processing. In this study, a visual measure of word and nonword reading efficiency—relying on lexical and phonological processing, respectively—was investigated for its ability to predict CI speech recognition outcomes, as well as to identify any improvements after implantation.

Methods: Twenty-four postlingually deaf adult CI candidates were tested on the Test of Word Reading Efficiency, Second Edition preoperatively and again 6 months post-CI. Six-month post-CI speech recognition measures were also assessed across a battery of word and sentence recognition.

Results: Preoperative nonword reading scores were moderately predictive of sentence recognition outcomes, but real word reading scores were not; word recognition scores were not predicted by either. No 6-month post-CI improvement was demonstrated in either word or nonword reading efficiency.

Conclusion: Phonological processing as measured by the Test of Word Reading Efficiency, Second Edition nonword reading predicts to a moderate degree 6-month sentence recognition outcomes in adult CI users. Reading efficiency did not improve after implantation, although this could be because of the relatively short duration of CI use.

Key Words: Cochlear implant—Cognition—Sensorineural hearing loss—Speech recognition.

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INTRODUCTION

Cochlear implants (CIs) are electrical prostheses that restore audibility to patients with moderate-to-profound sensorineural hearing loss (SNHL). By bypassing the inner ear, a CI stimulates the auditory nerve directly, providing restoration of speech input to the listener (1). Even so, postlingually deaf adult patients display significant variability in speech recognition after implantation, which is only partially understood. Most previous studies related to CI outcomes have focused primarily on demographic, audiologic, and surgical factors, or more directly on the quality of the signal delivered to the auditory nerve and cortex (2–4). Analyses of “bottom-up” processes related to the quality of the sensory input provided from CIs suggest that much of the variability in post-CI outcomes results from variability in the functionality of the auditory nerve, as well as the limitations of the electrode-nerve interface and relatively broad stimulation of the auditory nerve. For example, degeneration of spiral ganglion cells with prolonged auditory deprivation may affect auditory nerve response to CI stimulation (5). CIs can transmit the full range of frequencies that can be detected by a normally functioning ear, but fail to match the resolution of these transmitted frequencies to that of normal hearing. Moreover, CI listeners must process a spectrally degraded auditory signal as a result of spread of excitation at the electrode-nerve interface (6).

Although bottom-up processing explains a portion of the variability in speech recognition outcomes, it is also important to understand how “top-down” neurocognitive and language processing interact with the bottom-up information

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the brain receives to contribute to outcomes (7). A number of top-down processes have been found to explain speech recognition abilities under degraded listening conditions and/or specifically speech recognition outcomes in adult CI users, including working memory capacity (8), use of semantic context (9), inhibition-concentration (10), and nonverbal reasoning (11). The focus of the current study was on phonological and lexical processing, and the extent to which preoperative phonological and lexical processing skills predict post-CI outcomes. Successful spoken word recognition relies on rapid mapping of auditory input onto lexical representations stored in long-term memory (8,12). In individuals with hearing loss, however, that mapping can be challenging, effortful, and inefficient, resulting in a mismatch between the auditory speech input and the listener's linguistic (lexical and phonological) representations in long-term memory (13). In addition, the experience of a prolonged period of moderate-to-profound SNHL may actually contribute to poorer efficiency of linguistic processing, especially phonological processing because of degraded phonological representations (13–17). This effect of SNHL on phonological representations may be caused by a lack of reinforcement and disuse of linguistic representations during prolonged deafness. In auditory phonological tasks, hearing loss compromises the quality of incoming auditory input, so accurately mapping these degraded signals onto long-term memory becomes less efficient (18). Further, one study has supported that the duration of deafness partially accounts for the degree of deterioration in phonological representations that postlingually deaf adults experience, as the neurologic frameworks within the prefrontal and visual cortices that support phonological processing progressively degenerate over time (19).

The strategy deaf adults adopt during processing of speech may also reflect the robustness of phonological representations. Although still not completely understood, the "dual stream model" of language processing provides a framework for understanding individual differences in language processing (20,21). Based on neuroimaging studies, the dual stream model involves a "dorsal stream," that involves mapping sound to articulation (and, hence, a phonological emphasis), and a "ventral stream," which involves more direct mapping of sound to meaning (and, hence, a lexical emphasis). Tasks that specifically rely on phonological processing can be accessed visually through either written language or facial movements, and primarily stimulate the left-lateralized dorsal route in the brain. Individuals have been shown to utilize this dorsal route at the onset of deafness, and even recruit occipitotemporal regions of the brain to reinforce phonological representations through combined audio-visual communication modalities, such as lip reading (19,22). However, as these phonological representations gradually decay, deaf individuals activate the alternative ventral route and resort to lexicosemantic (meaning-based) processes to adapt. Moreover, because degraded phonological representations impede efficient phonological processing, deaf individuals experience a disrupted ability to quickly and accurately decipher nonwords.

Phonological processing abilities have been found to relate to speech recognition outcomes in experienced CI users, in studies using both auditory (18) and nonauditory tasks (19,22) of phonological processing. Speed or efficiency of lexical access has also been found to relate to speech recognition outcomes (9,23). Thus, assessing the quality of preserved phonological and lexical representations may shed light on understanding and being able to predict post-CI outcomes. The Test of Word Reading Efficiency, second edition (TOWRE-2; 24) is a measure of nonword and word reading efficiency, relying upon phonological decoding processes and direct access to mental representations of words, respectively (23). As a nonauditory testing measure, TOWRE-2 is administered visually, which removes any concerns regarding the confounding factor of audibility in patients with hearing loss. The test is divided into two subtests: one subtest consists of a list of real words (sight-word efficiency [SWE]), whereas the other subtest consists of a list of nonwords (phonological decoding efficiency [PDE]). The reader is given 45 seconds to read out loud the contents on each list as quickly and accurately as possible. The SWE portion evaluates the ability to quickly and directly retrieve lexical items from long-term memory. A previous TOWRE-2 study found the SWE subtest to be significantly related to sentence recognition accuracy scores in experienced CI users (23). The PDE portion, on the other hand, is more representative of phonological decoding. Interestingly, the PDE subtest was not found to be significantly related to sentence recognition accuracy in the previous study of experienced CI users. These previous findings suggest that sentence recognition relies more on lexical access efficiency than phonological decoding, at least in experienced CI users. In this study, we sought to enroll a group of preimplant CI candidates and test the hypothesis that preoperative TOWRE-2 scores on both real-word reading efficiency and nonword phonetic decoding would be predictive of speech recognition outcomes 6 months after CI surgery. We predicted that phonetic decoding efficiency would be a greater predictor of early speech recognition outcomes in this population, because new CI users are undergoing the process of re-mapping the new auditory signals delivered by their CIs to previously established phonological representations in long-term memory.

The current study also sought to evaluate any improvements in phonological and lexical processing after restoration of audibility through a CI. Older adult patients with hearing loss are at greater risk of developing cognitive impairment than older adults with normal hearing, though the underlying mechanisms linking hearing loss and cognitive decline are not clearly understood (25). Older adults with hearing loss have shown greater loss of memory and executive function. Fortunately, growing evidence suggests that restoration of audibility through CIs may support improvements in neurocognitive functions (26). Of particular relevance to this study but less studied, restoration of audibility through a CI may improve some aspects of nonauditory linguistic processing, such as verbal fluency (27,28) and verbal working memory (e.g., the Visual Reading Span; 29). Thus, in this study, we further sought to test the hypothesis that reading efficiency and phonetic decoding skills would improve from preoperatively to 6 months after receiving CIs, because restored audibility and better access to spoken language may allow CI individuals to access phonological and lexical representations more efficiently.

METHODS

Participants

Twenty-four adult CI candidates were assessed, both preoperatively and 6 months after CI surgery. All participants were native American English speakers who had obtained at least a high school degree or equivalent. All were screened to satisfy criteria for basic cognitive and linguistic functioning. This included a raw score of ≥24 on the Mini-Mental State Examination (MMSE; 30), presented in a combined auditory and visual format with instructions in writing, to rule out any significant cognitive impairment. Participants were required to have scores exceeding a standard score of 70 on the Wide Range Achievement Test, fourth edition (WRAT; 31). The WRAT was developed to measure general reading and language proficiency, and consists of a list of 70 items that includes real words, letters, and irregular words presented in order of increasing difficulty and phonological complexity. Participants read the list at their own pace. The WRAT raw score represents untimed word reading ability. The study was approved by the local Institutional Review Board. Participants provided written, informed consent and were incentivized monetarily for their participation.

Real Word and Nonword Reading Efficiency

The Test of Word Reading Efficiency, second Edition (TOWRE-2; 24), was administered to CI candidates both preoperatively and 6 months after implantation. This test is delivered in a visual format. Divided into two sections each performed over 45 seconds, one subtest measures SWE, which involves reading out loud as many real words as possible from a list of 108 real words. The number of correctly identified real words determines the raw score for SWE. The other subtest measures PDE, which involves reading out loud as many nonsensical nonwords as possible from a list of 66 items. Accuracy is assessed by how many nonwords the reader was able to correctly produce. A total score was also calculated based on the total combined number of words and nonwords correctly read out loud.

Speech Recognition Measures

A battery of sentence and word recognition measures were obtained 6 months after implantation. The Harvard Standard sentences include 28 semantically meaningful sentences consisting of 5 keywords delivered by a male speaker (32). The Harvard Anomalous sentences are comprised of semantically anomalous sentences (33). PRESTO sentences consist of 30 high-variability sentences produced by different male and female speakers originating from various geographic locations across the United States (34). Isolated word recognition scores were obtained in quiet using the Central Institute of the Deaf (CID W-22) words (35,36). These sentence and word stimuli were presented in quiet at 68 dB sound pressure level (SPL) over a loudspeaker 1 m in front of the participant. Additional sentence recognition measures were collected from the electronic medical record to represent sentence recognition tests used in clinical settings. These included AzBio sentences presented at 60 dB SPL in both quiet and noise (+10 dB multitalker babble) (37). Preoperative AzBio scores were also collected in order to evaluate improvements in speech recognition after implantation. For each measure, an accuracy score was calculated based on the percent total words correct.

Data Analyses

To test the hypothesis that preoperative TOWRE-2 scores would correlate with postimplantation sentence recognition scores, one-tailed Spearman rho correlations were utilized to relate these measures; Spearman correlations were used because speech recognition outcomes were not normally distributed, and one-tailed tests were used with the prediction that better TOWRE-2 performance would be associated with better speech recognition. To test the hypothesis that TOWRE-2 scores would improve 6 months post-CI, a Wilcoxon

TABLE 1. *Demographics for individual participants*

Participant	Gender	Age (y)	Duration of Hearing Loss (y)	Side of Implant	Etiology of Hearing Loss	Better Ear PTA (dB HL)
1	F	76	61	Left	Mèniére's disease	101.25
2	M	60	48	Right	Blunt trauma	112.5
3	M	55	42	Right	Progressive as adult	80
4	M	67	27	Right	Noise	77.5
5	M	82	62	Left	Progressive as adult, noise	87.5
6	M	74	44	Right	Genetic, noise	91.25
7	F	77	14	Left	Genetic, progressive as adult	53.76
8	F	61	41	Right	Noise	73.75
9	F	58	52	Right	Genetic, progressive as adult	120
10	M	75	35	Right	Progressive as adult, noise	76
11	F	54	54	Right	Genetic, sudden hearing loss	106.25
12	M	67	22	Right	Genetic, progressive as adult	78
13	M	65	40	Left	Progressive as adult, Mèniére's disease	65
14	M	65	15	Left	Progressive as adult, noise	80
15	F	53	41	Right	Genetic, progressive as adult	80
16	M	73	33	Right	Genetic, progressive as adult	66
17	F	49	49	Right	Progressive as child	102
18	M	79	49	Left	Noise	85
19	M	65	30	Right	Genetic, progressive as adult	68
20	F	76	26	Right	Progressive as adult	88
21	M	77	25	Left	Progressive as adult	71
22	F	54	35	Right	Noise, sudden hearing loss	70
23	M	74	22	Right	Progressive as adult	53
24	M	69	14	Right	Progressive as adult	63

PTA: pure-tone average; HL: hearing level.

TABLE 2. *Group means for demographic, audiologic, and screening measures for all 24 participants*

	Minimum	Maximum	Mean	SD
Age (y)	49	82	66.9	9.6
Better-ear PTA (dB HL)	53	120	81.2	17.5
WRAT (standard score)	70	120	95.8	13.9
MMSE (raw score)	24	30	28.3	1.88
Hearing loss duration (y)	14	62	37.9	14.3

Note: PTA = pure-tone average across 500, 1,000, and 2000 Hz.

MMSE indicates Mini-Mental State Examination; PTA, pure-tone average across; SD, standard deviation; WRAT, Wide Range Achievement Test.

Signed Rank test was conducted to compare preoperative and postoperative TOWRE-2 scores; this test was used because TOWRE-2 scores were also not normally distributed. Finally, a Wilcoxon Signed Rank test was also carried out to compare preoperative and postoperative AzBio scores.

RESULTS

Twenty-four postlingually deaf adults (9 female/15 male) participated in this study. Individual participant demographic and audiologic measures (including self-reported duration since onset of hearing loss) are shown in Table 1, with group mean data shown in Table 2. Participants completed preoperative speech recognition measures in best-aided listening condition that demonstrated candidacy for receiving CIs, including the AzBio sentences in quiet for all participants (n = 24; M = 30.9%; standard deviation [SD] = 25.7) and in noise for some participants who only qualified for implantation in noise (n = 12; M = 30.5%; SD = 19.9). All participants received a unilateral CI (22 Cochlear Americas, 1 Advanced Bionics, and 1 Med-EL devices); 22 were tested with their contralateral hearing aids (i.e., bimodal condition) at 6 months post-CI.

Results from one-tailed Spearman rho correlations among pre-CI TOWRE-2 and post-CI speech recognition scores are shown in Table 3. No significant correlations were observed between real word SWE scores and post-CI outcomes across all speech recognition measures. However, nonword PDE scores showed significant correlations of medium correlation size (rho = 0.3–0.5) with sentence recognition accuracy on Harvard Standard sentences, PRESTO, AzBio sentences in quiet, and AzBio sentences in noise. The total TOWRE-2 preoperative scores were also correlated with sentence recognition accuracy on Harvard Standard sentences, PRESTO, and AzBio sentences in noise.

A Wilcoxon signed rank test was used to compare preoperative TOWRE-2 scores to those collected 6 months after implantation, with results shown in Table 4. There was no significant difference between performance on preoperative and postoperative scores on the SWE subtest, the PDE subtest, or the total TOWRE-2 score. Finally, participants demonstrated improvements in AzBio sentence recognition in quiet, with group mean scores improving from 30.9% (SD = 25.7) to 69.5% (SD = 26.7), which was a significant improvement based on Wilcoxon Signed Rank test ($p < 0.001$).

DISCUSSION

This study sought to investigate whether efficiency of lexical access and phonological processing on a visual reading task could predict speech recognition outcomes in postlingually deaf patients after treatment with cochlear implantation. The efficiency of lexical access and PDE were assessed with real word (SWE) and nonword reading efficiency (PDE) subtests, respectively, of the TOWRE-2. Preoperative nonword reading efficiency (PDE) scores were significantly correlated with (i.e., moderately predictive of) sentence recognition measures obtained 6 months post-CI. Specifically, stronger nonword reading was related to more accurate sentence recognition on the Harvard Standard sentences, PRESTO, and AzBio sentences, both in quiet and in noise. However, no significant correlation was exhibited between scores of real word reading (SWE) and any measure of sentence recognition. Isolated word recognition scores on CID words were also not associated with TOWRE-2 scores.

The results of the current study partially corroborate findings from a previous cross-sectional study that demonstrated a relation between SWE performance and sentence recognition outcomes in experienced CI patients (23). In contrast with the previous study with experienced CI users, our longitudinal findings here in newly implanted CI users showed that PDE scores obtained before surgery were associated with sentence recognition outcomes 6 months after surgery. The differing findings in the relations between SWE and PDE subsets and sentence recognition outcomes for experienced CI users and new CI users may suggest that

TABLE 3. *Results of spearman correlation analyses among speech recognition scores post-CI and pre-CI TOWRE-2 scores*

	TOWRE-2 Words (SWE)		TOWRE-2 Nonwords (PDE)		TOWRE-2 Total	
Speech Recognition (% Words Correct)	Correlation Coefficient Rho	*p*	Correlation Coefficient Rho	*p*	Correlation Coefficient Rho	*p*
CID words	0.069	0.378	0.260	0.115	0.277	0.101
Harvard standard	0.097	0.326	**0.414**	**0.022**	**0.364**	**0.040**
Harvard anomalous	0.043	0.421	0.260	0.109	0.218	0.153
PRESTO	0.097	0.327	**0.434**	**0.017**	**0.380**	**0.034**
AzBio quiet	0.027	0.449	**0.346**	**0.049**	0.258	0.111
AzBio noise	0.132	0.27	**0.422**	**0.020**	**0.404**	**0.025**

Note: Correlation coefficients, and p values are bolded where significant at $p < 0.05$.

TABLE 4. *Group mean pre-CI and post-CI scores on TOWRE-2 test, as well as p* values of Wilcoxon signed rank tests comparing pre-CI and post-CI performance

		Mean	SD	*P*
TOWRE-2 Words (SWE)	Pre-CI	76.0	10.8	0.79
	Post-CI	75.5	11.5	
TOWRE-2 Nonwords (PDE)	Pre-CI	37.5	13.76	0.92
	Post-CI	37.5	14.49	
TOWRE-2 Total	Pre-CI	113.5	20.5	0.57
	Post-CI	113.0	21.84	

different factors may support spoken language processing at different time points after implantation. CI users require adjustment periods of several months to adapt to the degraded signal quality of their devices (14,19). We propose that because preoperative PDE scores showed a stronger relation with sentence recognition outcomes 6 months after surgery, adaptation processes in new CI users may rely very heavily on phonological decoding to understand speech. That is, new CI users rely heavily on adapting to the novel CI input by re-mapping the acoustic-phonetic information to existing phonological representations in long-term memory. In contrast, more experienced CI users would have had more time to adapt to their devices, and perhaps are better able to efficiently map the degraded auditory input onto lexical representations in long-term memory.

The second hypothesis was that phonological and lexical processing—as assessed by the TOWRE-2—would improve from preoperative testing to 6 months after cochlear implantation. This prediction stemmed from previous research that showed that certain neurocognitive and linguistic functions, such as verbal working memory, concentration, information-processing speed, and verbal fluency have been shown to improve in new CI users (26,38). However, counter to our prediction, no improvement was shown in TOWRE-2 performance. A possible reason for this finding could be that 6 months is not long enough to see measurable improvements in phonological or lexical processing. Reassessing reading efficiency capabilities 12 months or longer after implantation may yield observable improvements in phonological processing. Recent findings from experienced CI users revealed a mean SWE score of 78.2, a mean PDE score of 42.0, and a total TOWRE-2 average of 120.2 (23), all of which were significantly higher based on independent samples t-tests (all p values < 0.05) than those demonstrated by the CI candidates in this study, whose average scores on these measures were 76.0, 37.5, and 113.5, respectively. It is also worth noting that a group of older normal-hearing peers in that previous study demonstrated a mean SWE score of 83.3, a mean PDE score of 43.7, and a total TOWRE-2 average of 127 (23), which also were higher than TOWRE-2 scores of the participants in this study (all $p < 0.05$). Although it is possible that the stronger scores observed in those previous experienced CI users and normal-hearing peers are because of other differences between those groups and the current group (e.g., socioeconomic status or cognitive abilities), it is also possible that significant improvements in TOWRE-2 performance will be seen in our group of new CI users after a longer duration of CI experience.

Phonological representations deteriorate in part because of the degradation of neural pathways that support the phonological loop and other downstream pathways of phonological processing. In some cases of prolonged hearing loss, Lazard and Giraud (22) have even observed neural rearrangement and recruitment of the right temporo-occipital lobe as a cortical maladaptation to reduced auditory input and overreliance on communicating through reading and writing. Patients who adjusted to their hearing loss by communicating through lip reading displayed less of this maladaptation, and more preserved left lobe functionality for language comprehension, and furthermore, these individuals exhibited better post-CI outcomes. Individual differences in adaptive strategies to hearing loss may also, at least in part, explain the relation between reading efficiency and sentence recognition outcomes observed in the current study. What remains unclear, yet, is whether reinforcement with spoken language after receiving a CI can relocate language comprehension to the left hemisphere. Because patients with hearing loss are potentially subject to drastic modifications in neural circuitry, the underlying phonological processes themselves may experience more enduring changes that cannot be reversed within a short-term timespan like 6 months.

Another possible interpretation of a lack of improvement in TOWRE-2 scores at 6 months of CI use is that reading efficiency simply does not change significantly as a result of increased auditory access to spoken language through a CI. Perhaps the processing skills that relate to reading words and nonwords do not overlap sufficiently with processing of auditory speech input to result in any significant impact on reading efficiency. The greatest improvements in neurocognition because of improved audibility through a hearing aid or CI that have been demonstrated in the literature tend to be on tasks that place demands directly on auditory processing of stimuli. In other words, increased auditory access through a CI may lead to improvements on cognitive tasks that require auditory processing, rather than leading to a true improvement in underlying cognitive-linguistic processing skills. For example, an older study demonstrated that administering hearing amplification to a group of hearing-impaired adults produced improvement on cognitive measures for one-third of the participants (39). This finding was further supported by a study that found similar improvement on MMSE scores by 3 months after provision of hearing aids (40). A more recent study in new CI users also suggested that improvements on a screening task of cognition might be mostly attributable to improvements in audibility (41). Assessing phonological and lexical processing skills with both auditory and nonauditory measures at additional time points after implantation would shed more light on modality-specific or modality-general changes after cochlear implantation.

There are significant clinical ramifications of our findings. Specifically, a single preoperative PDE score obtained from a visual measure of reading showed medium-sized associations with postoperative speech recognition outcomes

6 months after implantation. This finding is important considering that previous preoperative audiologic and demographic measures combined together typically only account for about 20% or less of the speech recognition outcome variability demonstrated (42). Thus, the TOWRE-2 may serve as a rapid test that could be implemented clinically as part of a battery of audiologic, demographic, auditory, language, and cognitive measures to help clinicians counsel patients regarding their likely CI outcomes. However, it should be noted that TOWRE-2 scores alone were only moderately predictive of sentence recognition scores, accounting for about 15% to 20% of the demonstrated outcome variability. Additional ongoing studies are required to determine which preoperative assessments, alone or in combination, are most high yield in accomplishing the goal of providing better prognostication and counseling to patients.

This study has several limitations. As noted above, testing new CI users only 6 months after implantation may have limited our ability to demonstrate any changes in efficiency of lexical and phonological processing. Following up with patients at additional time points longitudinally could elucidate more long-term benefits of receiving a CI. Furthermore, this study was limited by its relatively small sample size of only 24 participants. A larger group could help improve generalizability of findings to the broader population of postlingually deaf adults receiving CIs.

CONCLUSION

This study explored how lexical access and phonological decoding contributed to speech recognition outcomes in postlingually deaf CI candidates after 6 months of CI use. Nonword reading efficiency (i.e., phonological decoding ability) was better able to predict sentence recognition outcomes than lexical access efficiency, and this was true across several sentence recognition measures in quiet and in noise. No improvement of TOWRE-2 scores was found in patients from preoperatively to 6 months post-CI, but this may have been a result of the relatively short duration of CI use. Nonetheless, the relationship between phonological decoding ability and post-CI outcomes might be useful for clinical application as a very short and simple tool to help predict how well a CI candidate will adjust postoperatively.

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