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Published in:
Otology & Neurotology

DOI:
10.1097/MAO.0000000000002925

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Tamati, T. N., Vasil, K. J., Kronenberger, W. G., Pisoni, D. B., Moberly, A. C., & Ray, C. (2021). Word and Nonword Reading Efficiency in Postlingually Deafened Adult Cochlear Implant Users. *Otology & Neurotology*, *42*(3), E272-E278. https://doi.org/10.1097/MAO.0000000000002925

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Word and Nonword Reading Efficiency in Postlingually Deafened Adult Cochlear Implant Users

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Hypothesis: This study tested the hypotheses that 1) experienced adult cochlear implants (CI) users demonstrate poorer reading efficiency relative to normal-hearing controls, 2) reading efficiency reflects basic, underlying neurocognitive skills, and 3) reading efficiency relates to speech recognition outcomes in CI users.

Background: Weak phonological processing skills have been associated with poor speech recognition outcomes in postlingually deaf adult CI users. Phonological processing can be captured in nonauditory measures of reading efficiency, which may have wide use in patients with hearing loss. This study examined reading efficiency in adults CI users, and its relation to speech recognition outcomes.

Methods: Forty-eight experienced, postlingually deaf adult CI users (ECIs) and 43 older age-matched peers with age-normal hearing (ONHs) completed the Test of Word Reading Efficiency (TOWRE-2), which measures word and nonword reading efficiency. Participants also completed a battery of nonauditory neurocognitive measures and auditory sentence recognition tasks.

Results: ECIs and ONHs did not differ in word (ECIs: $M = 78.2$, $SD = 11.4$; ONHs: $M = 83.3$, $SD = 10.2$) or nonword reading efficiency (ECIs: $M = 42.0$, $SD = 11.2$; ONHs: $M = 43.7$, $SD = 10.3$). For ECIs, both scores were related to untimed word reading with moderate to strong effect sizes ($r = 0.43–0.69$), but demonstrated differing relations with other nonauditory neurocognitive measures with weak to moderate effect sizes (word: $r = 0.11–0.44$; nonword: $r = (–)0.15$ to $(–)0.42$). Word reading efficiency was moderately related to sentence recognition outcomes in ECIs ($r = 0.36–0.40$).

Conclusion: Findings suggest that postlingually deaf adult CI users demonstrate neither impaired word nor nonword reading efficiency, and these measures reflect different underlying mechanisms involved in language processing. The relation between sentence recognition and word reading efficiency, a measure of lexical access speed, suggests that this measure may be useful for explaining outcome variability in adult CI users. **Key Words:** Cochlear implant—Individual differences—Reading efficiency—Speech recognition.

Otol Neurotol **42:**e272–e278, 2021.

Cochlear implants (CIs) have been very successful in providing a restored sense of hearing and improved speech recognition to adults with severe-to-profound hearing loss (HL). However, enormous individual differences in speech recognition outcomes are routinely observed. Less than half of post-CI speech recognition outcome variability can be explained by traditional demographic, audiologic, and surgical factors (1,2), which has limited the abilities of clinicians and researchers to predict CI outcomes and patient benefits (3).

Recently, researchers have begun to investigate the underlying neural and cognitive mechanisms by which these traditional factors contribute to outcomes. CI users receive a speech signal that is degraded in spectro-temporal detail, and individual CI users differ in their ability to make use of neurocognitive processes and language knowledge to understand the degraded speech information (e.g., (4,5)).

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A.C.M. and C.R. received grant support from Cochlear Americas for an unrelated investigator-initiated study of aural rehabilitation.

Development of measures used in this study was supported by the National Institutes of Health, National Institute on Deafness and Other Communication Disorders Career Development Award 5K23DC015539-02 and the American Otological Society Clinician-Scientist Award to A.C.M. Preparation of this manuscript was supported in part by VENI Grant No. 275-89-035 from the Netherlands Organization for Scientific Research and funding from the President's Postdoctoral Scholars Program at The Ohio State University awarded to T.N.T.

The authors disclose no conflicts of interest.

DOI: 10.1097/MAO.0000000000002925

Successful spoken word recognition relies on the rapid mapping of acoustic information onto long-term memory representations (6,7). However, the processing of degraded acoustic information in speech is challenging and effortful, as the mismatch between the speech signal and long-term representations triggers explicit controlled information processing that relies on working memory (e.g., (6,8)). Mismatches also arise from degraded phonological representations in long-term memory, which impede efficient and effortless processing (e.g., (9,10)).

For adult CI users, poor phonological processing may be partially attributable to deterioration of phonological representations during periods of severe-to-profound HL (11−15). Phonological processing skills have been found to be related to speech recognition outcomes in experienced CI users, using auditory (16,17) as well as nonauditory tasks of phonological processing (12,18). Moreover, individual differences in the efficiency or speed of lexical access, measured through visual lexical decision and word naming tasks, have been found to be related to speech recognition in noise in adult CI users (19).

Assessing phonological processing skills may be useful in explaining outcomes, especially if the tasks involve nonauditory stimuli that can be used preoperatively to predict postoperative performance, without concern for the confounding factor of audibility. The main goal of the current study was to examine the single-word reading efficiency skills (e.g., timed reading of individual words and nonwords, without the context of a meaningful passage) and its relation to speech recognition outcomes in a group of experienced, postlingually deafened adult CI users. Reading efficiency captures aspects of accuracy and fluency of word and nonword reading, albeit without implying comprehension, and relies both on phonological decoding processes often for unfamiliar or nonwords, and direct access to mental representations of words for real words (20,21). Additionally, it may reflect a set of underlying cognitive-linguistic skills relevant to processing both orthographic and spoken language (22,23).

In the current study, adult CI users' reading efficiency was first compared with a control group of age-matched adults with normal hearing (NH) to establish CI users' performance on a task of reading efficiency relative to NH peers. We further identified the underlying neurocognitive skills involved in reading efficiency in adult CI users, and explored the relation with sentence recognition outcomes. We hypothesized that 1) reading efficiency would differ between adult CI users and NH older adults; 2) individual differences in reading efficiency among adult CI users would reflect basic, underlying neurocognitive skills; and 3) individual differences in reading efficiency among adult CI users would be related to sentence recognition outcomes.

METHODS

Participants

Forty-eight experienced, postlingually deaf adult CI users (ECIs) and 43 older adult peers with age-normal hearing (ONHs) participated in the current study. The ECI group included 23 females and 25 males, ages 45 to 83 years ($M = 66.8$; $SD = 10.2$), with a socioeconomic status (SES) of 6 to 64 ($M = 26.4$; $SD = 14.3$). The ONH group included 28 females and 15 males, 50 to 81 years ($M = 67.4$; $SD = 6.9$), with an SES of 9 to 64 ($M = 36.3$; $SD = 14.2$) and pure-tone average (PTA) of 6.25 to 33.75 dB HL ($M = 16.2$, $SD = 7.3$). NH was defined as four-tone (0.5, 1, 2 kHz) PTA of better than 25 dB HL in the better ear. Three participants were included based on a relaxed PTA criterion of 35 dB HL or better, to accommodate elderly participants. Participants' SES was calculated using a metric derived from (24), based on the occupational and educational level of the primary household income earner. Occupational and educational level are assigned to values on an eight-point scale, with ''8'' representing the highest levels, and multiplied to obtain the SES score (range of scores: 1−64). Higher scores indicate higher SES. All demonstrated cognitive scores above passing criteria (≥ 24) on a written version of the Mini Mental State Examination (MMSE); ECI participants had MMSE raw scores of 25 to 30 ($M = 28.7$, $SD = 1.4$) and the ONH group had MMSE raw scores of 26 to 30 ($M = 29.3$, $SD = 0.9$). Among ECIs, 34 had 1 CI and 14 were bilateral users. Nineteen wore a hearing aid (HA) in the contralateral ear at the time of testing, while 15 did not wear a HA. At the time of testing, all ECIs had more than 1 year of CI use. All wore their typical hearing devices, including any contralateral HAs, during all testing. All participants were native English speakers, with at least a high-school diploma or equivalent. Demographic information is summarized in Table 1.

The current study was approved by The Ohio State University Institutional Review Board. All participants provided informed, written consent, and received $15 per hour for participation.

Measures and Procedures

Reading Efficiency

Reading efficiency was assessed using the Test of Word Reading Efficiency, Second Edition (TOWRE-2; (26)). The TOWRE-2 measures single-word, context-free reading accuracy, and fluency with two subtests that assess rapid real word reading (sight word efficiency (SWE)) and nonsense word reading (phonological decoding efficiency (PDE)). Participants were asked to read as many real words as possible in 45 seconds from a 108-word list, or as many nonsense words as possible from a 66-nonword list; Form A lists were used. Video recordings were used to transcribe responses by two trained scorers who had previously attained 95% agreement with an established reliable scorer of TOWRE-2 transcription. Each participant's TOWRE-2 was scored by one primary and one secondary scorer, and scores were measured for overall reliability. Scores with at least 95% inter-rater agreement were used for this measure. The SWE score was calculated as the number of words correctly read aloud and the PDE score was calculated as the number of nonsense words correctly read aloud. A total score was calculated by summing the SWE and PDE scores.

Nonauditory Neurocognitive Measures

ECIs completed a battery of nonauditory neurocognitive measures, assessing untimed word reading, vocabulary size, working memory, processing speed, concentration ability, and attentional/inhibitory control. These specific measures were included because they were previously identified as sharing underlying components with reading ability (untimed word

TABLE 1. *Demographic information and TOWRE-2 scores for ECI and ONH groups*

	ECI Postlingually Deafened Adults		ONH Age-normal Hearing		Effect Size on Group Differences
	M	SD	M	SD	Cohen's d
Demographic information					
Age	66.8	10.2	67.4	6.9	0.07
SES (out of 64)	26.4	14.3	36.3	14.2	0.69
MMSE (raw)	28.7	1.4	29.3	0.9	0.51
Better ear PTA (dB HL)	99.5	18.5	16.2	7.3	5.92
WRAT (raw)	41.9	6.9	45.2	5	0.55
Age at first CI	59.8	12.2			
Duration HL to CI (yr)	32.2	18.7			
TOWRE-2 reading fluency scores					
Sight word efficiency (SWE)	78.2	11.4	83.3	10.2	0.47
Phonological decoding efficiency (PDE)	42.0	11.2	43.7	10.3	0.16
Total	120.2	19.5	127.0	16.6	0.38

reading) or as underlying skills involved in reading efficiency (22). Nonverbal intelligence was also assessed to determine the possible contribution of domain-general mechanisms underlying the above processes.

Untimed reading ability was assessed using the Word Reading subtest of the Wide Range Achievement Test, 4th edition (27). For the 70-item untimed Word Reading task, participants read letters, regular words, and irregular words listed in order of increasing difficulty. The items progressed in difficulty by decreasing familiarity and increasing phonological complexity. Raw scores were used as a measure of untimed word reading ability.

Vocabulary size, indicative of an individual's lexical/semantic knowledge and lexical connectivity, was measured using the WordFam Word Familiarity Questionnaire (28), which entails rating familiarity of a set of 150 words on a scale from 1 (no familiarity) to 7 (high familiarity). Words represent high, medium, and low familiarity words based on normative data. The mean score across all items on the WordFam questionnaire was used as a measure of vocabulary size.

Working memory capacity was assessed using a visual digit span task, based on the original auditory digit span task from the Wechsler Intelligence Scale for Children, Third Edition (WISC-III). Participants reproduced visual lists of (2–7) ordered digits by tapping the digits in a 3×3 matrix on the computer touch screen. Total correct items (sequences) was used for analysis.

A computerized Stroop test (http://millisecond.com), based on the original Stroop test by (30), was used to obtain measures of processing speed, concentration ability, and attentional/inhibitory control, which are likely to contribute to reading efficiency in the timing and coordination of core processes used to ensure rapid and efficient reading. Participants pressed either a key on a keyboard corresponding to the font color of a color word (e.g., red) or a colored rectangle presented on the computer screen. Response times for both congruent (matching color word and font color) and incongruent word trials (mismatching color word and font color), as well as a control condition in which a colored rectangle was presented, were collected. Response times from the control, congruent, and incongruent trials were used as measures of processing speed, concentration ability, and inhibitory control, respectively.

The Raven's Progressive Matrices test was used to obtain a global measure of nonverbal intelligence (31). Participants completed incomplete visual patterns on a touchscreen monitor by selecting the best option from a closed-set of alternatives. Scores were number of correct items in 10 minutes.

Sentence Recognition Measures

Sentence recognition ability in quiet was assessed in ECIs using three sentence recognition tasks, which included Harvard Standard Sentences (32,33), Harvard Anomalous Sentences (34), and Perceptually Robust English Sentence Test Open-set (PRESTO) Sentences (35). Harvard Standard sentence materials consisted of 28 semantically meaningful sentences containing 5 keywords produced by a single male talker. The Harvard Anomalous sentences consisted of 28 semantically anomalous sentences, based on the original Harvard sentences, produced by a single male talker. Finally, PRESTO test materials consisted of 30 high-variability sentences, produced by different male and female talkers from different geographical regions of the United States. In each task, sentences were presented at 68 dB A via a loudspeaker, approximately 1 m from the participant at 0 degree azimuth. Participants repeated the sentences aloud to the best of their ability. Oral responses were recorded scored offline for the total number of words correct out of total number of words in the sentences.

Data Analysis

Group differences in reading efficiency: To examine group differences, means and standard deviations for ECI and ONH groups were calculated for the SWE, PDE, and Total TOWRE-2 efficiency measures. A separate one-way analysis of covariance was carried out with each of the three efficiency measures as the dependent variable and group as the between-subject variable. SES and age were added as covariates to account for potential effects on reading efficiency. Neurocognitive factors underlying reading efficiency in ECIs: To examine the relations between reading efficiency and neurocognitive abilities in ECIs, Pearson correlations were calculated between TOWRE-2 efficiency scores and scores on nonauditory neurocognitive measures for ECIs. Relation between reading efficiency and sentence recognition in ECIs: Pearson correlations were carried out on TOWRE-2 efficiency measures and sentence recognition scores to determine the relation between reading efficiency and sentence recognition outcomes in ECIs.

TABLE 2. *Pearson correlations between TOWRE-2 scores and scores on nonauditory neurocognitive measures in ECIs*

		WRAT (Untimed Word Reading)	WordFam (Vocabulary Size)	Digit Span (Working Memory)	Stroop Control (Processing Speed)	Stroop Congruent (Concentration)	Stroop Incongruent (Inhibitory Control)	Raven's (Nonverbal Reasoning)
TOWRE-2 reading fluency scores								
SWE	*r*	0.43	0.25	0.11	−0.33	−0.41	−0.19	0.44
	p	0.003[a]	0.102	0.458	0.028[a]	0.006[a]	0.215	0.003[a]
PDE	*r*	0.69	0.42	0.31	−0.23	−0.43	−0.15	0.27
	p	<0.001[a]	0.004[a]	0.034[a]	0.137	0.003[a]	0.315	0.071
Total	*r*	0.65	0.38	0.24	−0.32	−0.48	0.2	0.41
	p	<0.001[a]	0.010[a]	0.102	0.033[a]	0.001[a]	0.195	0.005[a]

SWE, Sight word efficiency; PDE, Phonological decoding efficiency.
[a] $p < 0.05$.

RESULTS

Group differences in reading efficiency: mean reading efficiency scores for ECIs and ONHs are presented in Table 1. For SWE scores, the group (ECI versus ONH) effect was not significant ($F(1,86) = 2.4$, $p = 0.125$, $\eta_p^2 = 0.027$), after controlling for SES and age. SES was a significant covariate ($F(1,86) = 8.2$, $p = 0.005$, $\eta_p^2 = .087$), but age was not significant ($F(1,86) = 3.7$, $p = 0.058$, $\eta_p^2 = .041$). For PDE scores, the group (ECI versus ONH) effect was not significant ($F(1,86) = .1$, $p = 0.815$, $\eta_p^2 = .001$), after controlling for SES and age. SES was not a significant covariate ($F(1,86) = 3.2$, $p = 0.076$, $\eta_p^2 = .036$), but age was significant ($F(1,86) = 8.6$, $p = 0.004$, $\eta_p^2 = 0.091$). For the total score, the group (ECI versus ONH) effect was also not significant ($F(1,86) = 1.2$, $p = 0.286$, $\eta_p^2 = 0.013$), after controlling for SES and age. SES was a significant covariate ($F(1,86) = 7.9$, $p = 0.006$, $\eta_p^2 = 0.084$), as well as age ($F(1,86) = 8.6$, $p = 0.004$, $\eta_p^2 = 0.091$).

Neurocognitive factors underlying reading efficiency in ECIs: Table 2 shows a summary of the results of Pearson correlations between reading efficiency scores and nonauditory neurocognitive measures for ECIs. SWE scores were significantly related to untimed word reading (WRAT), processing speed (Stroop control), concentration (Stroop congruent), and nonverbal reasoning (Raven's), but not working memory (Digit Span), vocabulary size (WordFam), or inhibitory control (Stroop incongruent). PDE scores were significantly related to untimed word reading (WRAT), vocabulary size (WordFam), concentration (Stroop congruent), and working memory (Digit Span), but not processing speed (Stroop control), inhibitory control (Stroop incongruent), or nonverbal reasoning (Raven's). Finally, the total reading efficiency score was significantly related to untimed word reading (WRAT), vocabulary size (WordFam), processing speed (Stroop control), concentration (Stroop congruent), and nonverbal reasoning (Raven's), but not inhibitory control (Stroop incongruent) or working memory (Digit Span).

Relation between reading efficiency and sentence recognition in ECIs: Table 3 shows the results of Pearson correlations between the three reading efficiency scores and auditory sentence recognition accuracy scores for ECIs. SWE and total scores were significantly related to Harvard Standard, Harvard Anomalous, and PRESTO sentences. PDE scores were not significantly related to any sentence recognition scores.

DISCUSSION

The current study examined reading efficiency in a group of experienced, postlingually deafened adult CI

TABLE 3. *Pearson correlations between TOWRE-2 scores and sentence recognition scores in ECIs*

		Sentence Recognition		
		Harvard Standard	Harvard Anomalous	PRESTO
TOWRE-2 reading fluency scores				
SWE	*r*	0.36	0.42	0.40
	p	0.015[a]	0.004[a]	0.006[a]
PDE	*r*	0.25	0.20	0.23
	p	0.097	0.183	0.126
Total	*r*	0.35	0.36	0.37
	p	0.018[a]	0.016[a]	0.014[a]

SWE, Sight word efficiency; PDE, Phonological decoding efficiency.
[a] $p < 0.05$.

users using the TOWRE-2. First, the reading efficiency skills of adult CI users were assessed relative to older NH peers. Contrary to our initial prediction, reading efficiency did not significantly differ between experienced adult CI users and older NH adults, when controlling for age and SES. As discussed above, the fidelity and specificity of phonological representations, underlying reading efficiency, have been previously found to be negatively impacted by HL (11–15); however, this was not directly tested in this study. Further, auditory phonological processing has generally been shown to be delayed or atypical in adult, postlingually deaf CI users, especially in those with poorer outcomes, compared with NH adults, when assessed using auditory lexical decision and nonword repetition tasks (17,36). One account of our conflicting findings is that the speech delivered by a CI, albeit degraded, is sufficient to maintain reading efficiency skills for many implant users with extended CI use, although this is not possible to determine without measures of reading efficiency before HL and/or implantation. In fact, recent studies have suggested that cochlear implantation may help improve cognitive functioning in CI users (37). Additionally, despite long-term acquired HL, some ECIs may have been able to maintain stronger and more robust phonological representations through visual-based phonological processing (i.e., lip-reading) during everyday speech communication activities (e.g., (38,39)). Finally, although we are assuming that degraded representations would be reflected on an assessment of reading efficiency, it is possible that the TOWRE-2 measure does not fully reflect the robustness the phonological representations, given that other processes are likely contributing to performance and use of compensatory strategies (10,18,40).

Second, the current study investigated the factors underlying reading efficiency in the CI users. By examining the associations between the basic, underlying neurocognitive skills and each TOWRE-2 score, we can better understand the underlying skills that each score assesses and, by doing so, the factors underlying any relations between TOWRE-2 scores and sentence recognition outcomes. As expected, all three TOWRE-2 scores reflected basic reading and neurocognitive skills, but the scores showed differing relations with neurocognitive measures. Relations between real word reading efficiency (SWE) and untimed word reading, processing speed, concentration ability, and nonverbal reasoning confirmed that the TOWRE-2 SWE measure reflects the ability to quickly identify and directly access stored lexico-phonological representations of words in long-term memory. In contrast, nonword reading efficiency (PDE) scores were related to untimed word reading, vocabulary size, concentration ability, and working memory. The total score was related to untimed word reading, vocabulary size, processing speed, concentration ability, and nonverbal reasoning. Taken together, these findings demonstrate that the SWE and PDE subtests and the total score reflect different underlying mechanisms, which may be more or less relevant to explaining individual differences in speech recognition outcomes in adult CI users.

Finally, the current study examined the relation between individual differences in reading efficiency and sentence recognition outcomes in adult CI users. Sentence recognition accuracy scores were found to be significantly related to real word reading efficiency (SWE) and the total score, combining real word and nonword reading efficiency, but not to nonword reading efficiency (PDE). These findings suggest that CI users with faster reading for real words (SWE) may demonstrate more efficient lexical access, promoting fluent processing of speech. Previous research has suggested that faster lexical access speed, through better signal quality or stronger phonological representations, promotes better speech recognition abilities because the listener has more cognitive resources available for additional processing of speech in context or resolving additional ambiguities (e.g., (6,41,42)).

Contrary to our initial expectations, nonword reading efficiency (PDE) was not found to be related to sentence recognition accuracy in this group of ECIs. Phonological decoding crucially depends on access to intact phonological representations of speech in working memory. If, as mentioned above, individuals use working memory to compensate for degraded phonological representations, these individuals may similarly achieve high sentence recognition accuracy but at the cost of more effortful processing. An alternative explanation of the lack of relation between PDE scores and sentence recognition accuracy is skills involved in phonological decoding may be most relevant to lower-level mapping of acoustic-phonetic information onto phonological representations. The ECI users tested in the current study have had substantial experience with their CIs, and have likely achieved stable mappings between the degraded acoustic-phonetic information and internal representations. Relations between nonword reading efficiency and sentence recognition may emerge in recently implanted CI recipients, who are still involved in the perceptual learning process and are building stable mappings. In the present study, we demonstrated that stronger non-auditory processing of real words is related to sentence recognition in CI users. Although nonauditory lexical processing would not reflect the additional challenges arising from the degraded CI signal, nonauditory measures of lexical access capture a common linguistic mechanism underlying rapid access to lexical representations of words in long-term memory (20,21). Importantly, variance associated with this underlying skill appears to be related to individual differences in speech recognition accuracy in experienced CI users.

Clinical Implications

The findings from the current study suggest that a nonauditory test of reading efficiency may be useful for understanding speech recognition outcomes in postlingually deafened CI users. In particular, the measure of reading efficiency for real words (SWE) subtest of the

TOWRE-2 appears to capture a common underlying information processing skill that is related to individual differences in sentence recognition accuracy. This measure may therefore be more useful for assessing and tracking the underlying linguistic skills of patients with HL than lexical processing tasks that rely on the processing of auditory signals.

Limitations

The current study was limited in its use of only experienced CI users and may not reflect the impact of severe-to-profound HL on phonological processing that is experienced by patients before cochlear implantation. While our results suggest that CI use may help to maintain or restore compromised phonological representations and provide normal access to lexical representations, future research should collect TOWRE-2 reading efficiency scores from CI candidates both preoperatively and postimplantation. Tracking changes will help to determine the extent to which cochlear implantation improves the underlying processing skills reflected in measures of reading efficiency performance, and will determine the value of TOWRE-2 assessed pre-operatively in predicting speech recognition outcomes in this patient population.

Another limitation of the current study is that reading efficiency involves a large set of underlying cognitive-linguistic skills-based phonological processing and lexical access, as described above, and also likely reflects academic learning, experience, and practice. Deficiencies in any one of these core components and/or experience may therefore affect reading efficiency. As such, future research should also compare the TOWRE-2 scores to other measures of phonological processing for orthographic and spoken language, to better understand the relation between reading efficiency and sentence recognition in adult CI users.

CONCLUSIONS

In the current study, the speed and efficiency of reading familiar words out loud was related to several measures of speech recognition in experienced, postlingually deaf adult CI users. This finding suggests that efficiency of lexical access, measured by the TOWRE-2 sight word reading subtest, may reflect core, underlying operations of speech recognition that are modality-independent. Additional research examining how nonauditory information processing skills relate to speech recognition will provide new knowledge of the core foundational information-processing factors that underlie individual differences in CI outcomes. Furthermore, these studies may yield new tools that could be used for clinical and research purposes to understand the variability in speech recognition outcomes in adult CI users.

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