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Research Article

Assessing Higher Order Language Processing in Long-Term Cochlear Implant Users

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Purpose: The purpose of this study was to describe and explain individual differences in complex/higher order language processing in long-term cochlear implant (CI) users relative to normal-hearing (NH) peers.
Method: Measures of complex/higher order language processing indexed by the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) Core Language subtests were obtained from 53 long-term (≥ 7 years) CI users aged 9–29 years and 60 NH controls who did not differ in age, gender, or nonverbal IQ. Vocabulary knowledge and fast, automatic language processing (rapid phonological coding, verbal rehearsal speed, and speech intelligibility) were also assessed.
Results: CI users showed weaker performance than NH controls on all CELF-4 Core Language subtests. These differences remained for Formulated Sentences and Recalling Sentences even when vocabulary knowledge was statistically controlled. About 50% of the CI sample scored within the range of the NH sample on Formulated Sentences and Recalling Sentences, while the remaining 50% scored well below the NH sample on these subtests. Vocabulary knowledge, rapid phonological coding, verbal rehearsal speed, and speech intelligibility were more strongly correlated with CELF-4 subtest scores in the CI sample than in the NH sample.
Conclusions: Weaknesses in complex, higher order language processing shown by a subgroup of CI users compared to NH peers may result from delays in fast, automatic processing of language. These at-risk domains of language functioning could serve as targets for novel interventions for deaf children who experience suboptimal spoken language outcomes following cochlear implantation.

The use of cochlear implants (CIs) is now a well-established medical intervention to provide auditory stimulation and sensory experience for prelingually deaf children after a period in early life without exposure to sound. Many deaf children with CIs are able to develop speech and language skills, such as vocabulary and speech recognition in quiet settings, within the range of same-aged normal-hearing (NH) peers (Niparko et al., 2010). However, some children with CIs show marked delays compared with NH peers in multiple domains of speech and language outcomes, including speech recognition, vocabulary, nonword repetition, and reading (Pisoni, Kronenberger, Roman, & Geers, 2011). The causes of the large individual differences and variability in speech and language outcomes in CI users are still unclear even after several decades of research on CIs (Pisoni, Kronenberger, Harris, & Moberly, 2018). This lack of knowledge represents a significant barrier to progress, especially for children with CIs who achieve speech and language scores on the low end of the range of performance after several years of CI use (Pisoni et al., 2018).

Spoken language processing includes a combination of both simple/basic and complex/higher order information-processing activities (Language and Reading Research Consortium, 2015). Simple/basic language abilities include vocabulary knowledge (knowledge of meaning of words) and fund of information (factual verbal knowledge encoded in language form). Simple/basic language abilities are assessed using brief verbal or pictorial stimuli and require single-word or pointing (e.g., to a picture) responses. As a

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result, they reflect language-based knowledge (words or facts) with minimal concurrent demands on comprehension, organization, concept formation, syntax, or production of a complex response (e.g., expressive language explaining an answer). In contrast, complex/higher order language abilities, such as discourse (Language and Reading Research Consortium, 2015), require the integration and coordination of both receptive and expressive language abilities, the processing of syntax and semantics, and the organization, integration, and coordination of linguistically complex information in the service of comprehension and/or expression. Outcome measures that assess domains of complex higher order language processing go beyond basic speech recognition or verbal knowledge (fund of information), emphasizing instead how well the CI user is able to extract intended meaning and ideas from spoken language and convey concepts and ideas expressively.

The most widely used and established conventional speech and language outcome measures for CI users reflect simple/basic speech and language skills such as speech recognition and vocabulary. In contrast, less attention has been focused on complex/higher order language abilities in CI users, although assessment of these abilities is critical in clinical and educational settings. In this study, we assessed higher order language skills in CI users and investigated neurocognitive factors associated with higher order language skills in an attempt to explain variability in higher order language processing.

Complex Higher Order Language Processing in Children and Adolescents With CIs

Many children with CIs who perform well on measures of simple/basic language skills such as vocabulary struggle with more complex higher order language processing. In one study, over half of a sample of children with CIs achieved age-appropriate vocabulary scores by kindergarten, but less than half of the sample was on par with NH peers in syntax, morphology, and other complex language skills (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). In another study, Geers, Nicholas, and Sedey (2003) found that over half of their sample of elementary school–age children with CIs scored within the range of NH peers on measures of expressive language, but less than half of the sample scored within the range of NH peers on measures that assessed aspects of higher order syntactic language.

Composite scores from global language batteries such as the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003) are typically used to characterize language functioning in CI samples (e.g., Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013). However, those composite scores may mask variability in specific domains of language functioning represented by specific subtests, particularly domains that involve challenging, complex, higher order language abilities such as spoken language comprehension (Spaulding, Plante, & Farinella, 2006). For example, Geers and Sedey (2011) found that a CELF subtest assessing comprehension of spoken paragraphs produced the lowest scores for CI samples relative to NH peers, although two thirds of the CI sample scored in an average range on a CELF language composite score. Tomblin, Spencer, and Gantz (2000) found that a CELF subtest emphasizing production of syntax produced the lowest score for CI users relative to the average percentile for NH peers, although the CI sample mean scores on less complex language subtests were within the range of NH peers by adulthood. Thus, examination of specific subtest scores on complex higher order language measures such as the CELF may enhance our understanding of language outcomes following implantation.

Models of Neurocognitive Processing and Language Outcomes in CI Users

In addition to describing complex higher order language outcomes in samples of prelingually deaf, early implanted children and adolescents with CIs compared to NH peers, it is important to understand factors contributing to variability in the development of higher order language processing within the population of children and adolescents who receive CIs. For example, demographic and hearing history variables including higher nonverbal intelligence, higher parent education level, higher parental income, female gender, and younger age at implantation have been associated with better CELF scores in children and adolescents with CIs (Geers et al., 2009; Ruffin et al., 2013). However, even after accounting for demographic and hearing history, much of the variance in higher order language outcomes in children with CIs remains unexplained.

In order to better explain variability in language outcomes in populations at risk for language delays (including CI users), several neurocognitive processing models have been proposed. Models such as the Ease of Language Understanding model (Rönnberg et al., 2013), the Framework for Understanding Effortful Listening model (Pichora-Fuller et al., 2016), and the Auditory Neurocognitive Model (Kronenberger & Pisoni, 2018) all share the broad premise that speech-language processing relies on two processing channels: (a) a fast, automatic information-processing channel in which phonological, lexical, and semantic attributes of language are processed rapidly with little conscious effort and processing resources and (b) a slow, effortful information-processing channel in which executive resources are consciously applied to process information that is too challenging or complex to be managed by the fast, automatic processing channel, such as the recognition of underspecified and sparsely coded signals from a CI in challenging listening environments.

For children with CIs, it is likely that both information-processing channels contribute to spoken language processing to a greater degree than they do in NH peers. CI users show greater variability than NH peers in fast, automatic processing, because of large individual differences in the quality of phonological and lexical representations of language in long-term memory (LTM) in CI users (Smith, Pisoni, & Kronenberger, 2019). This variability in fast, automatic processing in CI users is related to speech recognition and sentence repetition skills (Smith et al., 2019). In addition, the slow, effortful channel involving compensatory executive functioning skills such as verbal working memory (WM) is likely to be more heavily used by CI users than NH peers under challenging speech recognition and spoken language processing conditions because of the increased demands of such tasks on limited cognitive resources for CI users (Kronenberger, Henning, Ditmars, & Pisoni, 2018). Consequently, CI users engage slow, effortful, conscious processing mechanisms much more often than NH peers to compensate for poorer fast, automatic processing of language (Smith et al., 2019).

Studies have found much stronger associations between speech and language processing and executive functions (WM, fluency–speed, and inhibition–concentration) in children with CIs compared to NH peers, consistent with the hypothesis that CI users are more dependent than NH peers on slow, effortful executive processing for language skill development (e.g., Beer, Kronenberger, & Pisoni, 2011; Kronenberger, Colson, Henning, & Pisoni, 2014; Pisoni et al., 2011). Importantly, findings also support strong associations between measures of executive functioning and higher order language comprehension (Beer et al., 2011; Pisoni et al., 2011). However, although prior research has demonstrated a link between complex higher order speech and language outcomes and the slow, effortful processing channel (indexed by executive functioning) in CI users (e.g., Kronenberger et al., 2014, 2018; Rönnberg et al., 2013), there has been relatively little research on the variability of complex higher order speech and language outcomes and the fast, automatic processing channel in CI users.

Fast, automatic processing is likely to play a greater role in complex higher order language processing in CI users compared to NH peers, because the more spoken language CI users are able to process through the fast, automatic channel, the more cognitive resources they can allocate to effortful organization and comprehension of complex higher order language. Furthermore, fast, automatic language processing facilitates higher order language skills by allowing for greater throughput of linguistic information and concepts during real-time comprehension.

Fast, automatic processing of speech and language is dependent on the integrity of several core skills that reflect the ease and efficiency with which linguistic information is encoded and processed. Examples of core skills used in fast, automatic language processing include rapid phonological coding (the ability to quickly and accurately detect and perform mental operations such as decomposition and reassembly on speech signals, apart from their meaning), verbal rehearsal speed (vocal or subvocal repetition of verbal items as a way of maintaining sensory and lexical information in limited-capacity WM), and speech intelligibility (how well a person's speech is recognized by others during language production; Pisoni, Cleary, Geers, & Tobey, 1999). Although other measures of the fast, automatic channel of speech and language processing exist, these three core skill domains provide a broad representation of the core information-processing skills that support and facilitate fluent, automatic processing of receptive and expressive language.

Rapid phonological coding has been routinely assessed by nonword repetition tests (Gathercole & Baddeley, 1996). Although underspecified, coarsely coded phonological representations explain much of the variance on nonword repetition tasks (e.g., Nittrouer, Caldwell-Tarr, Sansom, Twersky, & Lowenstein, 2014), nonword repetition abilities in children with CIs are also related to how quickly, accurately, and efficiently children with CIs are able to process and encode speech and language (Smith et al., 2019). Verbal rehearsal speed, on the other hand, is estimated from measures of speaking rate (Hulme, Thomson, Muir, & Lawrence, 1984), which are associated with verbal WM in samples of CI users (Pisoni et al., 2011). Speech intelligibility is considered an index of global linguistic competence and reflects the automaticity of language processing through speech production (Pisoni et al., 1999). Research has demonstrated strong associations between measures of speech intelligibility and speech recognition, speech comprehension, word recognition, vocabulary knowledge, receptive and expressive language, and WM (Freeman, Pisoni, Kronenberger, & Castellanos, 2017; Montag, AuBuchon, Pisoni, & Kronenberger, 2014; Pisoni et al., 1999).

The current study was designed to investigate higher order language outcomes in prelingually deaf, long-term CI users, compared to NH peers, and to investigate associations between measures of fast, automatic language processing and higher order language outcomes in an effort to better understand the information-processing operations that contribute to outcomes. We expected that complex higher order language tasks would be particularly challenging for CI users (above and beyond basic vocabulary and knowledge) and that the proficiency level of the fast, automatic language processing channel (measured with rapid phonological coding, verbal rehearsal speed, and speech intelligibility) would be a critical factor in predicting complex higher order language processing outcomes in prelingually deaf, long-term CI users. Thus, our first hypothesis was that CI users would show weaker performance on measures of complex higher order language processing than NH controls, even after statistically controlling for basic vocabulary knowledge. Our second hypothesis was that correlations between vocabulary knowledge and measures of complex higher order language functioning would be significant but modest in CI and NH samples, reflecting the greater demands of higher order language processing above and beyond vocabulary knowledge. Our third hypothesis was that fast, automatic processing indexed by rapid phonological coding, verbal rehearsal speed, and speech intelligibility (process measures) would play a greater role in complex higher order language processing for CI users compared to NH peers, because the more verbal information the CI users can process through the fast, automatic channel, the more spare cognitive resources and capacity they will have left over for allocation to complex higher order language demands.

Method

Participants

Fifty-three children, adolescents, and young adults with long-term CI use (≥ 7 years, as defined in prior work; Kronenberger, Pisoni, Henning, & Colson, 2013; Ruffin et al., 2013; CI sample) and 60 NH peers (NH sample) participated in this study. Participants were recruited from a larger sample enrolled in a multiwave study of long-term CI users and NH peers (Kronenberger et al., 2013).

Inclusion criteria for the CI sample were severe-to-profound hearing loss (> 70 dB HL) prior to or at the age of 3;0 (years;months); cochlear implantation prior to the age of 7;0; use of a modern, multichannel CI system for ≥ 7 years; communication mode rated as "auditory–oral" (Geers & Brenner, 2003); and, at the time of testing, enrolled or living in an environment that encouraged the development and use of spoken language skills. Inclusion criteria for both the CI and NH samples were as follows: < 30 years of age, English as the primary language spoken in the household, no other neurological or neurodevelopmental disorders or delays documented in the medical chart or reported by parents, a nonverbal IQ ≥ 2 *SD*s below the normative mean (Wechsler Abbreviated Scale of Intelligence [Wechsler, 1999] Matrix Reasoning subtest *t* score ≥ 30), and completion of the primary speech and language measures for the study (Peabody Picture Vocabulary Test–Fourth Edition [PPVT-4], CELF-4, and McGarr Intelligibility). In addition, participants in the NH sample were required to pass a hearing screening in each ear individually (using Telephonics TCH-50P headphones in an Acoustic Systems RE243 soundbooth) at 20 dB HL at 500, 1000, 2000, and 4000 Hz.

Procedure

Study procedures were approved by the local institutional review board. Written consent and assent were obtained prior to administration of study procedures. Participants took part in two waves of data collection occurring approximately 2 years apart. Measures of verbal rehearsal speed, vocabulary, speech production, and complex higher order language processing were obtained in the first wave of data collection, whereas a measure of rapid phonological coding was obtained during the second wave. Assessments at each wave were performed in one to two visits to the laboratory consisting of about 4 hr each. All tests were administered by American Speech-Language-Hearing Association–certified speech-language pathologists using the same standard directions for both the CI and NH samples. All tests and directions in this study were administered using standard instructions, consisting of live-voice presentation in auditory–verbal format without the use of any sign language and with the examiner's face in view, with the exception of the nonword repetition test (see below). For all measures, higher scores indicate stronger performance on the construct measured.

Measures

Rapid Phonological Coding

The Children's Test of Nonword Repetition (Nonword Repetition; Gathercole & Baddeley, 1996) was used to obtain a measure of rapid phonological coding. Participants repeated spoken nonwords that were presented via audio recording in a quiet setting at 65 dB SPL using a high-quality loudspeaker located approximately 3 ft from the participant. Percentage of whole nonwords reproduced correctly was the dependent measure used in the present data analyses.

Verbal Rehearsal Speed

Verbal rehearsal speed was estimated using articulation rates of 36 sentences in the McGarr Sentence Intelligibility Test (McGarr, 1981). This test consists of meaningful English sentences that are three ("Feed the dog"), five ("He said he could go"), or seven ("The book is on the table") syllables in length. In this test, the examiner says each sentence aloud while showing participants a card with the printed sentence. Consistent with prior use of the McGarr Test with CI users (Pisoni et al., 2011), participants are presented with a printed sentence to reduce reliance on audibility or memory. Because the test sentences are simple in length and vocabulary and are read aloud as well as presented in printed form, the effects of audibility or reading proficiency on performance are minimized, although not totally absent. The participant is then asked to correctly repeat the sentence at their natural conversation rate. If the examiner judges the response as incorrect (i.e., the response contained a word omission, deletion, or substitution), the examiner repeats the sentence and asks the participant to repeat it again. Digital audio recordings were made of each participant's spoken sentence repetitions. Sentence durations, in seconds, were calculated using the mean durations for the three-, five-, and seven-syllable McGarr sentences at the first repetition. We used sentence duration scores for seven-syllable McGarr sentences as a measure of verbal rehearsal speed in the present analyses because the seven-syllable sentences provide a larger sample of speech with more variability in duration than the shorter sentence tasks (Pisoni & Cleary, 2003).

Speech Intelligibility

McGarr Speech Intelligibility scores were obtained using the method described by Montag et al. (2014): Each of the 36 McGarr sentences produced by a single CI user was independently transcribed by three undergraduate listeners (each listener transcribed all 36 sentences for the CI user). A different set of undergraduate listeners transcribed sentences for each CI user such that each undergraduate listener only transcribed the 36 McGarr sentences for one CI user (53 CI users × 3 undergraduates per user = 159 undergraduate listeners). One undergraduate listener transcribed each of the 36 sentences spoken from a single NH participant (a separate group of 60 undergraduate listeners, one for each NH speaker). Undergraduate listeners were native speakers of American English who participated in this study for partial course credit in an introductory psychology class or for a payment of $10. All listeners had NH (as assessed by a hearing screening consisting of pure tones presented at 25 dB HL at 500–4000 Hz in the right and left ears) and passed an orthographic transcription prescreening task to ensure orthographic transcription competence. None of the listeners reported any prior experience with deaf speakers or individuals who used a CI. The undergraduate listeners were seated at a computer screen and transcribed spoken utterances presented through high-quality headphones (Beyerdynamic DT-100-400OHM)) at a comfortable hearing level (approximately 60–65 dB SPL). Sentence intelligibility was calculated using the proportion of each participant's sentences that were perfectly transcribed (verbatim compared to the stimulus sentence) by all listeners. This rigorous "perfect-sentence intelligibility" criterion reduced ceiling effects in the NH sample and provided an index of fluent intelligibility of speech (Freeman et al., 2017).

Vocabulary Knowledge

Vocabulary knowledge was assessed with the PPVT-4 (Dunn & Dunn, 2007) standard score. In this test, participants are asked to identify which of four stimulus pictures best represents the meaning of a single word spoken by the examiner. Age norm-based standard score was the dependent measure used in the present analyses.

Complex Higher Order Language Processing

Complex higher order language processing was assessed with the CELF-4 (Semel et al., 2003). Participants were administered the six CELF-4 subtests required to obtain Core Language scores, depending on age: (a) Formulated Sentences, (b) Recalling Sentences, (c) Word Classes–Expressive, (d) Word Classes–Receptive, (e) Word Definitions, and (f) Concepts & Following Directions.

The six CELF-4 subtests used in this study require organization and application of language skills above and beyond verbal fund of information/knowledge alone. Formulated Sentences assessed the ability to produce syntactically/grammatically and semantically correct sentences based on a picture and a word spoken by an examiner. Because Formulated Sentences requires concurrent management of knowledge, grammar, sentence syntax, organized expression, and idea development, it reflected higher order language skills. Recalling Sentences assessed the ability to recall and repeat sentences of increasing lengths and syntactic complexity spoken by the examiner. Unlike conventional sentence repetition or speech intelligibility tests, Recalling Sentences requires substantial use of comprehension, verbal memory, and grammatical knowledge to provide support and retrieval cues for recall of increasingly complex sentences.

Word Classes–Expressive and Word Classes–Receptive assessed the ability to comprehend and explain associations between words.[1] In this task, participants choose two related words from a selection of choices presented by the examiner either visually or orally (receptive knowledge) and then say how those two words are related (expressive knowledge). Word Classes assesses higher order language skills of concept formation (knowing not only what the words mean but also how they are similar) and organized expression (constructing an expressive response that conveys an idea to the listener). Word Definitions assessed the ability to define words presented by the examiner in a sentence. In contrast to tests such as the PPVT-4, which require only a pointing response, Word Definitions requires application of higher order language skills including organized expression (constructing an expressive response that not only shows knowledge of a word but also provides the definition in a format that is understandable and accurate to the examiner) and comprehension (maintaining understanding of the overall meaning of the spoken response to ensure that it is accurate). Concepts & Following Directions assessed the ability to recall and follow spoken directions of increasing length and syntactic complexity by pointing to objects in pictures following the examiner's spoken instructions; it evaluates the higher order language skills of comprehension, concept formation, and conversion of verbal information into motor responses. The age norm-based scaled scores for each of the CELF-4 subtests were the dependent measures used in the present analyses; 21-year-old norms were used for subjects aged 21 years and older.

Data Analysis Approach

First, group comparisons of sample characteristics were computed using *t* tests. In order to test our first hypothesis that CI users would show greater delays in performance on specific subdomains of complex higher order language processing even after controlling for vocabulary, *t* tests and frequency distributions were used to compare CI and NH samples on CELF-4 subscale scores, and then analyses of covariance were used to compare groups on CELF-4 scores while statistically controlling for PPVT-4 scores. Next, Pearson correlations were used to test our second hypothesis that variability in vocabulary knowledge (PPVT-4) would show a significant but moderate association with CELF-4 higher order language scores. Pearson correlations were then used to test our third hypothesis that variability in fast, automatic processing involving rapid phonological coding (Nonword Repetition), verbal rehearsal speed (McGarr durations), and speech intelligibility (McGarr intelligibility) would show stronger associations with complex higher order language processing (CELF-4 scores) in CI users compared to NH controls. Scatter plots were created to display the form, direction, and strength of the associations between

[1]Word Classes–Receptive and Word Classes–Expressive are administered together as one subtest that yields both receptive and expressive scaled scores. We refer to them as separate subtests in this study to correspond with our emphasis of specific subdomains of higher order language processing as reflected by CELF-4 subtest scores.

rapid phonological coding, verbal rehearsal speed, and speech intelligibility and scores on subtests of complex higher order language processing. Statistical tests (t tests or correlations) were compared to two-tailed p values of .01 to evaluate statistical significance of all analyses using CELF-4 subtest scores, based on a Bonferroni correction (five CELF-4 subtests given at each age, since Concepts & Following Directions is given to 9- to 12-year-olds, whereas Word Definitions is given to 13-year-olds and older; $p = .05/5 = .01$). For other tests when CELF-4 scores were not used (each test provided one score), a two-tailed p value of .05 was used.

Results

Sample Characteristics

Table 1 summarizes descriptive characteristics of the two samples. Participants in the CI sample were, on average, 3.4 months old at onset of deafness and 36.0 months old at CI implantation and had used their CIs for a duration of 12.3 years at the time of initial testing. Because 83% of the sample was deaf at birth and the average age of onset of deafness was 3.4 months, duration of deafness and age at cochlear implantation were very highly correlated for all participants in the CI sample ($r = .91$, $p < .001$). Pre-implant unaided pure-tone average in the better hearing ear for frequencies of 500, 1000, and 2000 Hz was 106.7 dB HL (SD = 11.0). The preferred modality of communication for all participants in the CI sample was auditory–oral. CI and NH samples did not differ on age, gender, income, or nonverbal IQ (see Table 1). Chronological age was not significantly related (Pearson correlations; all $ps > .05$) to PPVT-4 or CELF-4 scores (as expected, since those scores are already normed for age); age at implantation in the CI sample was also unrelated (all $ps > .05$) to PPVT-4 or CELF-4 scores (tables of these correlations are available from the authors on request).

Comparison of CI and NH Samples on Complex Higher Order Language Processing

Table 2 summarizes performance on measures of complex/higher order language processing (CELF-4 subtest scores) as well as measures of rapid phonological coding (Nonword Repetition), verbal rehearsal speed (McGarr durations), speech intelligibility (McGarr intelligibility), and vocabulary knowledge (PPVT-4) for the CI and NH samples. The CI sample scored significantly lower than the NH sample on all six CELF-4 subtests; these differences remained on the CELF-4 subtests Formulated Sentences and Recalling Sentences after statistically controlling for PPVT-4 score, but not on the Word Classes–Expressive, Word Classes–Receptive, Word Definitions, or Concepts & Following Directions subtests.

Furthermore, frequency distributions divided by sample (CI and NH) for performance on the CELF-4 Formulated Sentences and Recalling Sentences subtests revealed two subgroups in the CI sample (see Figure 1). For the Formulated Sentences subtest shown in Panel A, 53% (n = 28/53) of the CI sample scored within the NH sample range of 9–16; for Recalling Sentences shown in Panel B, 47% (n = 25/53) of the CI sample scored within the NH sample range of 7–19. Furthermore, within the range of the NH sample, the distribution of the NH and CI samples was roughly normal for the Formulated Sentences and Recalling Sentences subtests. However, a second subgroup of the CI sample scored below the range of the NH sample and showed a positive skew (particularly on the Recalling Sentences subtest), with more participants scoring at the low end of the CELF-4 scaled score range. In fact, seven participants in the CI sample received a scaled score of 1 on the Formulated Sentences subtest, and nine participants in the CI sample received a scaled score of 1 on the Recalling Sentences subtest (six of the participants in the CI sample received a scaled score of 1 on both subtests).

Table 1. Sample demographics and hearing history.

Descriptive characteristic	CI sample (n = 53)		NH sample (n = 60)		
	M (*SD*)	Range	*M* (*SD*)	Range	*t*
Chronological age[a]	15.3 (4.8)	9.1–26.7	15.5 (4.6)	9.1–25.3	−0.2 (*ns*)
Age at implantation[b]	36.0 (20.2)	9.9–75.8	NA	NA	
Duration of CI use[a]	12.3 (3.8)	7.1–21.3	NA	NA	
Age of onset of deafness[b]	3.4 (8.3)	0–36	NA	NA	
Pre-implant PTA[c]	106.7 (11.0)	85.0–118.4	NA	NA	
Communication mode[d]	5.0 (0.0)	5–5	NA	NA	
Income level[e]	7.2 (2.5)	2–10	7.2 (2.6)	1–10	0.0 (*ns*)
Nonverbal intelligence[f]	55.1 (7.4)	32–68	55.4 (7.1)	38–70	−0.2 (*ns*)
				Fisher's exact *p*	
Gender (female/male)	24/29		33/27	.35	

Note. Degrees of freedom (*df*) for *t* tests = 111, except income level (*t*-test *df* = 100). *p* value (two-sided) for gender was obtained from a Fisher's exact test. CI = cochlear implant; NH = normal-hearing; *ns* = not significant at $p \leq .05$; NA = not applicable; PTA = pure-tone average.
[a]In years. [b]In months. [c]Pre-implant unaided pure-tone average for frequencies of 500, 1000, and 2000 Hz in dB HL. [d]Communication mode coded mostly sign (1) to auditory–verbal (6; Geers & Brenner, 2003). [e]On a 1 (*under $5,500*) to 10 (*$95,000+*) scale (Kronenberger et al., 2013). [f]Wechsler Abbreviated Scale of Intelligence Matrix Reasoning (*t* score).

Table 2. Comparison of groups on Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4), Nonword Repetition, McGarr durations and speech intelligibility, and Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4).

Measure	CI sample (n = 53) *M* (*SD*)	NH sample (n = 60) *M* (*SD*)	*t*
PPVT-4[a]	90.79 (19.39)	111.78 (15.23)	−6.44***
Nonword Repetition[b,c]	25.82 (19.34)	87.44 (9.45)	−17.84***
McGarr duration[d]			
7-Syllable	1.91 (0.37)	1.61 (0.14)	5.65***
McGarr Speech Intelligibility[e]	57.92 (17.82)	83.77 (5.81)	−10.62***
CELF-4			
Formulated Sentences[f]	8.06 (4.34)	12.33 (1.58)	−7.12***
Recalling Sentences[f]	6.43 (4.24)	11.48 (2.43)	−7.88***
Word Classes–Expressive[f]	9.02 (3.49)	12.32 (2.38)	−5.92***
Word Classes–Receptive[f]	8.58 (3.85)	12.47 (2.51)	−6.43***
Word Definitions[f,g]	9.31 (5.23)	13.42 (2.18)	−4.42***
Concepts & Following Directions[f,h]	8.32 (3.20)	11.14 (1.55)	−3.72**
	Marginal mean (*SE*)	**Marginal mean (*SE*)**	***F***
Formulated Sentences[f] Controlling for PPVT-4[a]	9.43 (0.36)	11.12 (0.33)	10.29**
Recalling Sentences[f] Controlling for PPVT-4[a]	7.85 (0.39)	10.23 (0.36)	17.08***
Word Classes–Expressive[f] Controlling for PPVT-4[a]	10.50 (0.28)	11.01 (0.26)	1.54
Word Classes–Receptive[f] Controlling for PPVT-4[a]	10.27 (0.28)	10.98 (0.26)	2.98
Word Definitions[f,g] Controlling for PPVT-4[a]	11.07 (0.47)	11.94 (0.42)	1.68
Concepts & Following Directions[f,h] Controlling for PPVT-4[a]	9.17 (0.54)	10.29 (0.54)	1.76

Note. Degrees of freedom (*df*) for *t* tests = 111, except for Word Definitions (*df* = 68) and Concepts & Following Directions (*df* = 42). CI = cochlear implant; NH = normal-hearing.

[a]Standard score. [b]Percent whole nonwords correct. [c]CI sample: n = 38; NH sample: n = 39. [d]In seconds. [e]Perfect-sentence speech intelligibility score % correct. [f]Scaled score. [g]CI sample: n = 32; NH sample: n = 38. [h]CI sample: n = 22; NH sample: n = 22.

** $p < .01$. *** $p < .001$.

Correlations Between Vocabulary and Complex Higher Order Language Processing

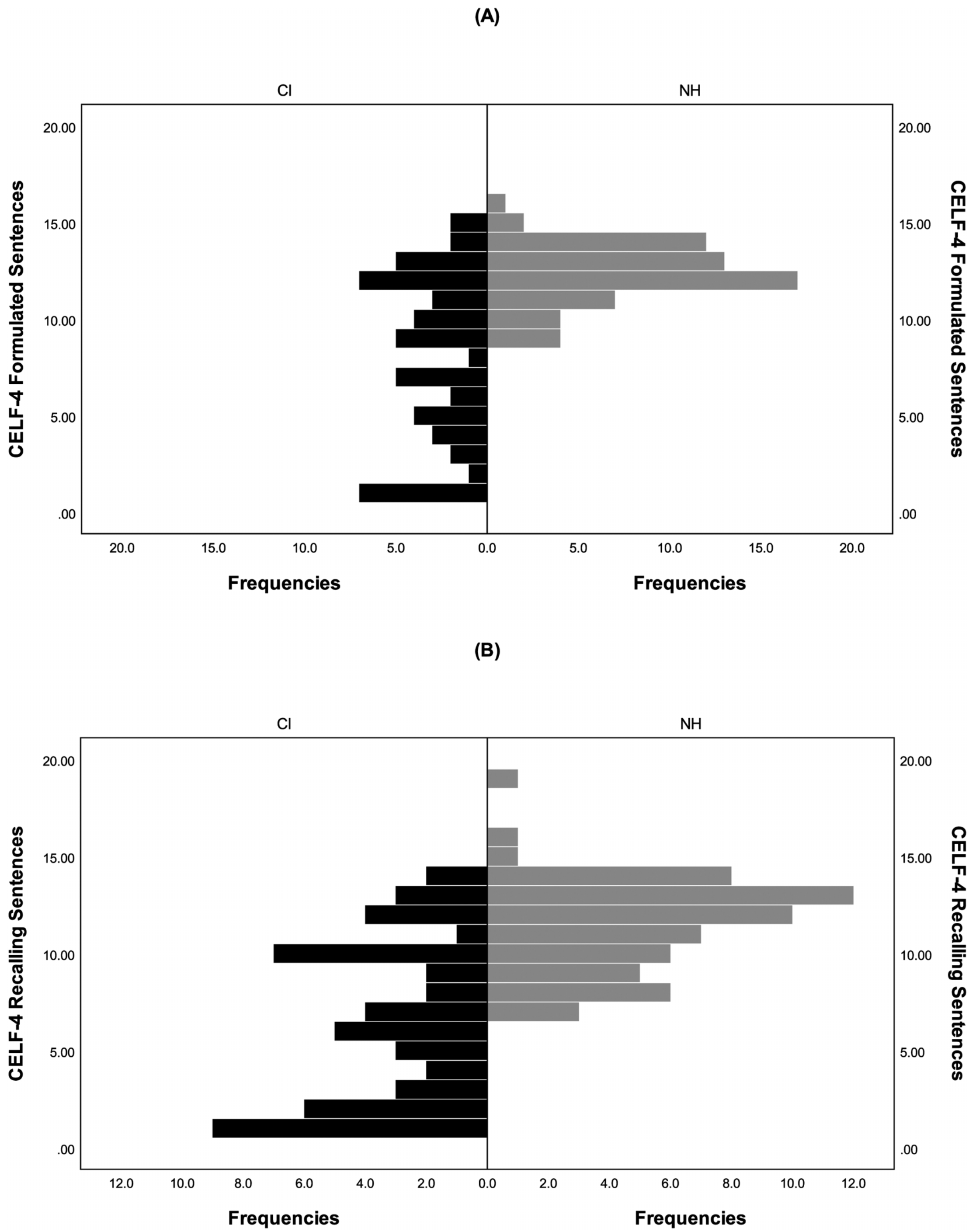
Table 3 summarizes correlations between vocabulary (PPVT-4) and complex higher order language (CELF-4 subtests). The association between PPVT-4 and CELF-4 scores was much stronger for the CI sample than for the NH sample, as shown by statistically significantly greater (by z test comparing strength of correlations) r values for the CI sample than for the NH sample for Formulated Sentences ($z = 5.00$, $p < .001$), Recalling Sentences ($z = 3.15$, $p < .01$), Word Classes–Expressive ($z = 2.11$, $p < .05$), Word Classes–Receptive ($z = 3.22$, $p < .01$), and Word Definitions ($z = 3.42$, $p < .001$).

Correlations Between Rapid Phonological Coding, Verbal Rehearsal Speed, Speech Intelligibility, and Complex Higher Order Language Processing

Table 4 summarizes the correlations computed between scores on rapid phonological coding (Nonword Repetition), verbal rehearsal speed (McGarr durations), speech intelligibility (McGarr intelligibility), vocabulary (PPVT-4), and complex higher order language processing (CELF-4) for the CI and NH samples. The associations between Nonword Repetition, PPVT-4, and CELF-4 scores were similar for the CI and NH samples, except for the association between Nonword Repetition and Recalling Sentences, which was stronger for the CI sample than for the NH sample ($z = 2.24$, $p < .05$; see Table 4).

Figure 2 shows scatter plots displaying the individual scores for Nonword Repetition on each x-axis with the data for the Formulated Sentences (Panel A) and Recalling Sentences (Panel B) subtests from the CELF-4 on the y-axis to illustrate the strength, direction, and nature/shape of the association between these variables for the CI and NH groups. Cross-hairs separate the individual scores into quadrants representing higher versus lower CELF-4 subscale scores (using the normative mean scaled score of 10 as the cutoff) and higher versus lower rapid phonological coding scores (using a cutoff value of 60% [identified by Smith et al., 2019, as reflecting an inflection point for nonword repetition test scores predicting sentence recognition at an NH level] as the cutoff). For Formulated Sentences (and, to a lesser extent, for Recalling Sentences), Nonword Repetition scores of 60% and higher were almost always associated with CELF-4 scores of 10 or higher (average to above average CELF-4 subscale scores; upper right quadrant) and almost never

Figure 1. Frequency distributions of scaled scores for the cochlear implant (CI) and normal-hearing (NH) samples on Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) Formulated Sentences in Panel A. Frequency distributions of scaled scores for the CI and NH samples on CELF-4 Recalling Sentences in Panel B.



associated with CELF-4 scores of lower than 10 (below-average CELF-4 scores; lower right quadrant). In contrast, Nonword Repetition scores of lower than 60% were associated with a much broader range of CELF-4 scores ranging from well below average (lower left quadrant) to well above average (upper left quadrant).

The associations between McGarr durations, PPVT-4, and CELF-4 subscale scores were also much stronger for the

Table 3. Correlations between Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4) and Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4).

Measure	CI sample (n = 53)	NH sample (n = 60)
	PPVT-4[a]	
CELF-4[b]		
Formulated Sentences[b]	.85***	.28
Recalling Sentences[b]	.78***	.41**
Word Classes–Expressive[b]	.84***	.67***
Word Classes–Receptive[b]	.90***	.69***
Word Definitions[b,c]	.89***	.51**
Concepts & Following Directions[b,d]	.52	.42

Note. Values are Pearson correlation coefficients. Note that tests significant at p < .05 are not reported due to Bonferroni correction. CI = cochlear implant; NH = normal-hearing.

[a]Standard score. [b]Scaled score. [c]CI sample: n = 32; NH sample: n = 38. [d]CI sample: n = 22; NH sample: n = 22.

**p < .01 ***p < .001.

Table 4. Correlations between Nonword Repetition, McGarr durations and speech intelligibility, Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4) scores, and Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4).

Measure	CI sample (n = 38)	NH sample (n = 39)
	Nonword Repetition[a]	
PPVT-4[b]	.49**	.60***
CELF-4[c]		
Formulated Sentences[c]	.55***	.24
Recalling Sentences[c]	.57***	.21
Word Classes-Expressive[c]	.35	.42**
Word Classes-Receptive[c]	.42**	.44**
Word Definitions[c,d]	.31	.40
Concepts & Following Directions[c,e]	.52	.31
	CI sample (n = 53)	**NH sample (n = 60)**
	McGarr 7-Syllable Durations[f]	
PPVT-4[b]	–.59***	–.05
CELF-4[c]		
Formulated Sentences[c]	–.57***	–.10
Recalling Sentences[c]	–.54***	–.02
Word Classes-Expressive[c]	–.51***	–.06
Word Classes-Receptive[c]	–.44**	.13
Word Definitions[c,g]	–.37	.01
Concepts & Following Directions[c,h]	–.52	–.11
	McGarr Speech Intelligibility[i]	
PPVT-4[b]	.46***	.13
CELF-4[c]		
Formulated Sentences[c]	.58***	.12
Recalling Sentences[c]	.51***	.12
Word Classes-Expressive[c]	.40**	.14
Word Classes-Receptive[c]	.44**	.10
Word Definitions[c,g]	.33	.04
Concepts & Following Directions[c,h]	.59**	.24

Note. Values are Pearson correlation coefficients. Note that tests significant at p < .05 are not reported due to Bonferroni correction. CI = cochlear implant; NH = normal-hearing.

[a]Percent nonwords correct. [b]Standard score. [c]Scaled score. [d]CI sample: n = 25; NH sample: n = 23. [e]CI sample: n = 14; NH sample: n = 16. [f]In seconds. [g]CI sample: n = 32; NH sample: n = 38. [h]CI sample: n = 22; NH sample: n = 22. [i]Perfect-sentence speech intelligibility score % correct.

**p < .01 ***p < .001.

Figure 2. Scatter plots of the association between Nonword Repetition scores and scaled scores on Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) Formulated Sentences in Panel A. Scatter plots of the association between Nonword Repetition scores and scaled scores on CELF-4 Recalling Sentences in Panel B. CI = cochlear implant; NH = normal hearing.

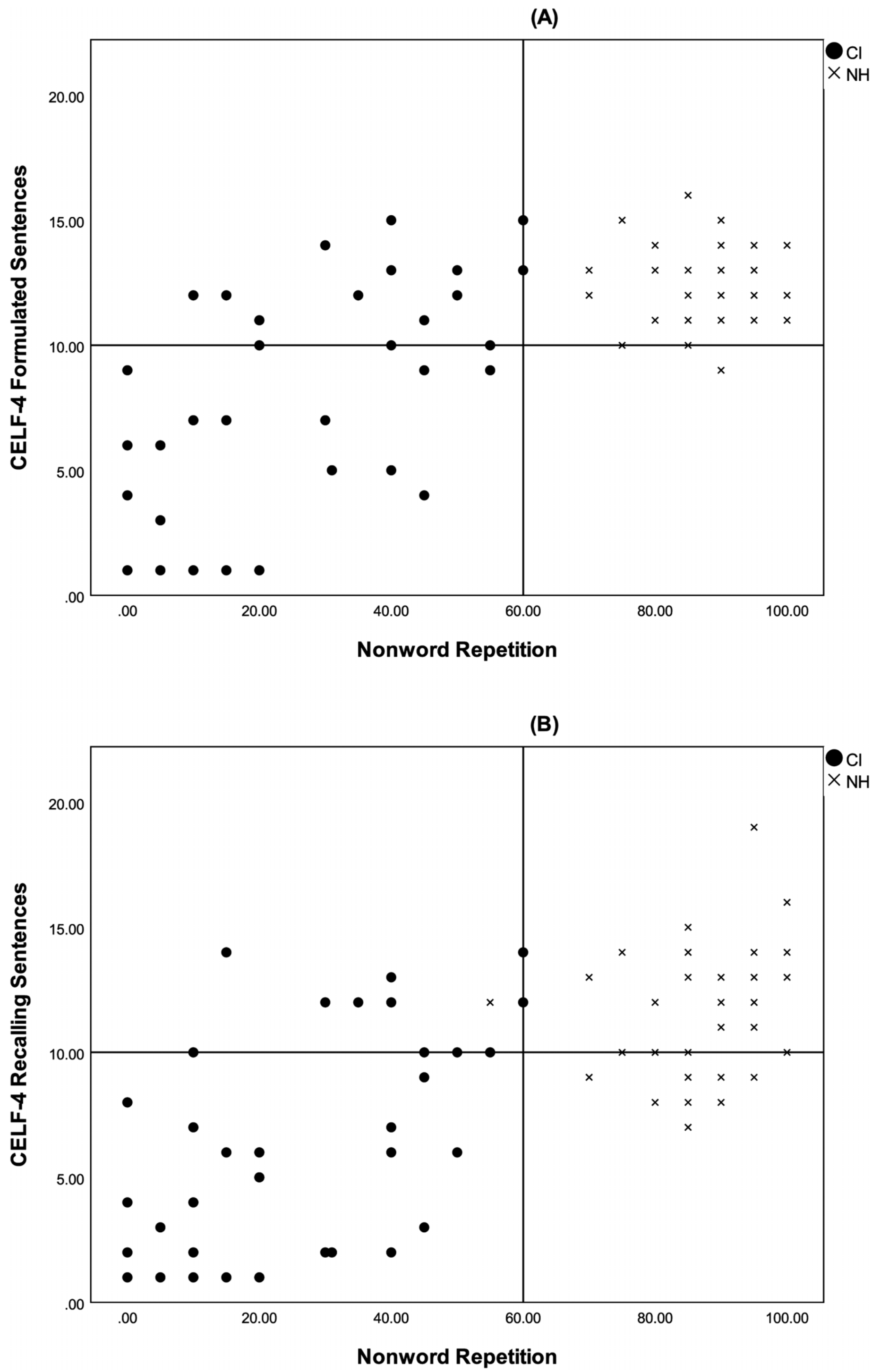
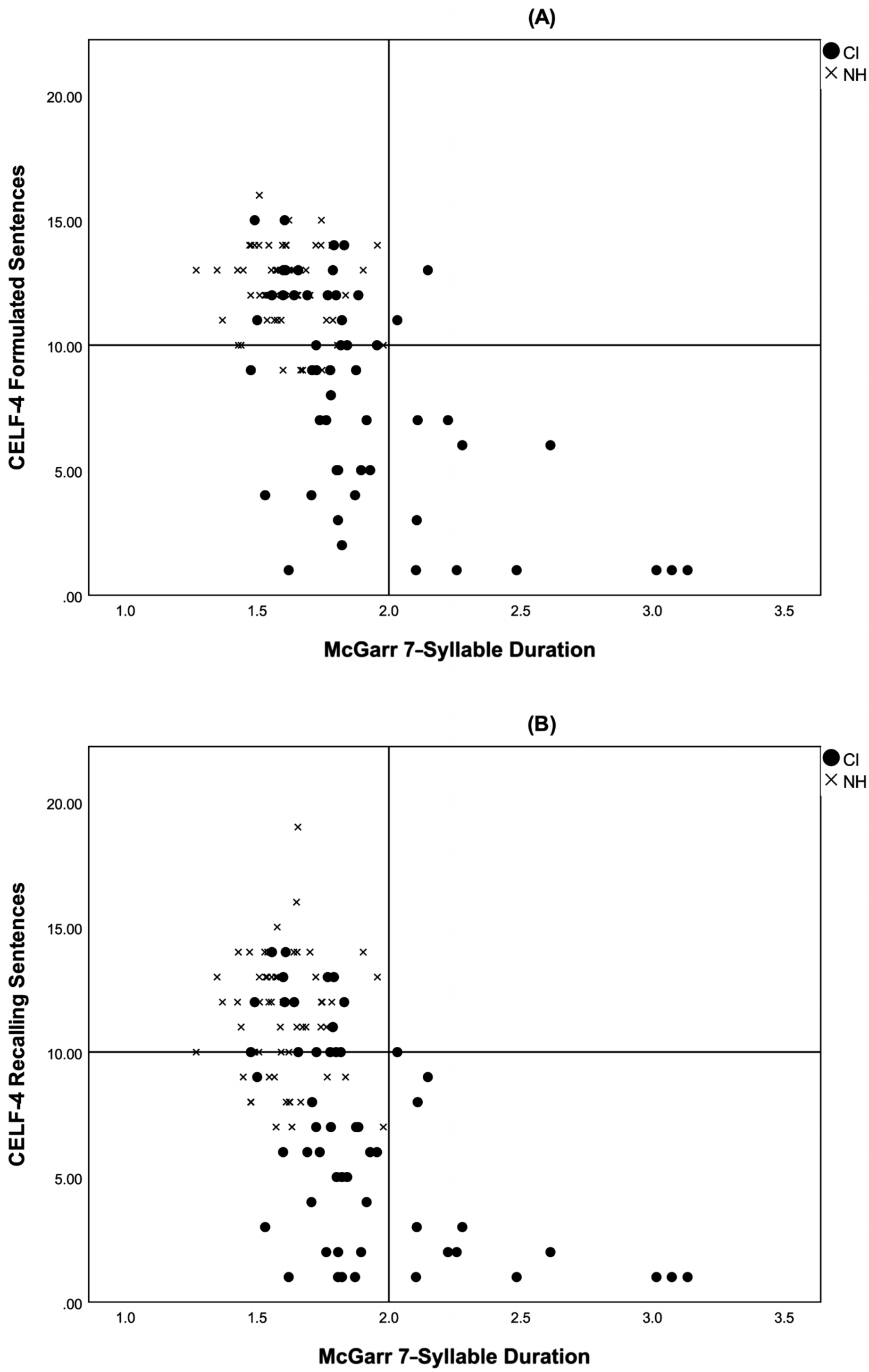


Figure 3. Scatter plots of the association between McGarr durations for seven-syllable sentences and scaled scores on Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) Formulated Sentences in Panel A. Scatter plots of the association between McGarr durations for seven-syllable sentences and scaled scores on CELF-4 Recalling Sentences in Panel B. CI = cochlear implant; NH = normal hearing.



CI sample than for the NH sample, as shown by the substantially larger negative r values for the CI sample than for the NH sample for PPVT-4 ($z = 7.07$, $p < .001$), Formulated Sentences ($z = 4.61$, $p < .001$), Recalling Sentences ($z = 4.22$, $p < .001$), Word Classes–Expressive ($z = 5.21$, $p < .001$), Word Classes–Receptive ($z = 4.87$, $p < .001$), Word Definitions ($z = 3.23$, $p < .01$), and Concepts & Following Directions ($z = 2.76$, $p < .01$; see Table 4). Figure 3 shows scatter plots displaying the individual scores for McGarr durations on each x-axis and data for the Formulated Sentences (Panel A) and Recalling Sentences (Panel B) subtests from the CELF-4 on the y-axis. Cross-hairs separate the individual scores into quadrants representing higher versus lower CELF-4 subscale scores (using the normative mean scaled score of 10 as the cutoff) and higher versus lower McGarr duration scores (using a cutoff value of 2 s for McGarr 7-Syllable Sentence Duration, based on data from Pisoni et al., 2011, showing that McGarr 7-Syllable verbal rehearsal speeds of 2 s and longer are highly unusual for an NH sample and typical for a CI sample). For both Formulated Sentences and Recalling Sentences, McGarr duration scores of 2 s and greater were almost always associated with below-average CELF-4 subscale scores of less than 10 (lower right quadrant) and almost never associated with CELF-4 scores of 10 or higher (upper right quadrant). In contrast, McGarr duration scores of faster than 2 s were associated with a much broader range of CELF-4 scores ranging from well below average (lower left quadrant) to well above average (upper left quadrant).

The associations between McGarr intelligibility and CELF-4 subscale scores were also stronger for the CI sample than for the NH sample, as shown in significantly higher positive r values for the CI sample than for the NH sample for Formulated Sentences ($z = 2.80$, $p < .01$) and Recalling Sentences ($z = 2.28$, $p < .05$; see Table 4). Figure 4 shows scatter plots displaying the individual scores for McGarr intelligibility on each x-axis with the data for the Formulated Sentences (Panel A) and Recalling Sentences (Panel B) subtests from the CELF-4 on the y-axis. Crosshairs separate the individual scores into quadrants representing higher versus lower CELF-4 subscale scores (using the normative mean scaled score of 10 as the cutoff) and higher versus lower McGarr intelligibility scores (using a cutoff value of 60% for speech intelligibility based on data showing that most NH children score above 60% and the average for children with CIs is 55%; Freeman & Pisoni, 2017). For both Formulated Sentences and Recalling Sentences, McGarr intelligibility of lower than 60% was almost always associated with below-average CELF-4 subscale scores of less than 10 (lower left quadrant) and almost never associated with CELF-4 scores of 10 or higher (upper left quadrant). In contrast, McGarr intelligibility scores of greater than 60% were associated with a much broader range of CELF-4 scores ranging from well below average (lower right quadrant) to well above average (upper right quadrant).

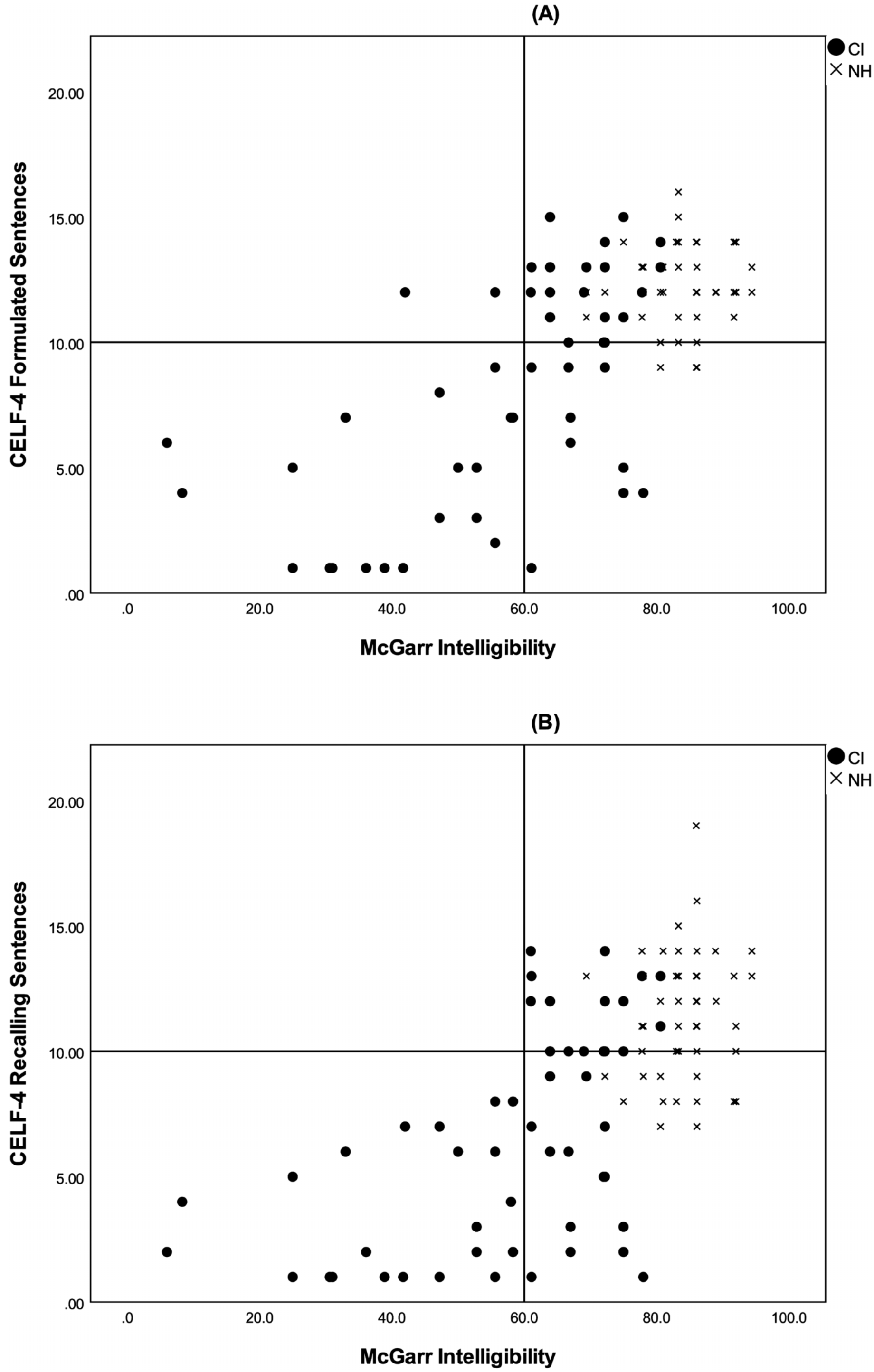
Discussion

This study was carried out to investigate complex higher order spoken language processing in CI users relative to NH peers and to explain variability in higher order spoken language processing within the sample of CI users. As hypothesized, CI users scored lower than NH peers on measures of complex higher order language skills measured by CELF-4 subtests. Lower scores obtained on Formulated Sentences and Recalling Sentences in the CI sample compared with NH peers remained significant even after controlling for vocabulary knowledge (PPVT-4).

Formulated Sentences and Recalling Sentences differ from the other four CELF-4 Core Language subtests because they place greater information-processing demands on complex organizational strategies used in language production, comprehension, and real-time processing of language. For example, in the Formulated Sentences subtest, participants must generate and construct increasingly complex grammatically correct and semantically meaningful sentences based on pictures and word prompts; in doing so, participants must identify, recall, and organize sequences of words from the mental lexicon in order to represent a concept. For Recalling Sentences, participants must repeat back sentences that increase in linguistic complexity throughout the subtest; this subtest places heavy demands on multiple language processing subdomains including speech recognition, comprehension, grammar, and short-term verbal memory. In contrast, CELF-4 subtests such as Word Classes and Word Definitions, while also demanding higher order language processing in the form of concept formation and/or organized expression, place more emphasis on static verbal knowledge/fund of information, with fewer demands on real-time complex-inferential language processing. Thus, the CELF-4 subtests may be considered as falling along a gradient/continuum of higher order language processing, with Word Classes and Word Definitions not as far along the "higher order" continuum (but involving more higher order processing than a simple vocabulary or fund of information subtest such as the PPVT-4) and Recalling Sentences and Formulated Sentences farther along the "higher order" continuum.

Because the Formulated Sentences and Recalling Sentences subtests require participants to organize, coordinate, and store linguistically complex information in active verbal WM, these findings suggest that complex higher order language processing involving the comprehension of linguistically complex information is particularly challenging for CI users, apart from difficulties with basic language knowledge such as vocabulary. Additional support for this interpretation may be found in the performance of the CI sample on the CELF-4 Word Definitions subtest, which places fewer demands on higher order processing and was the highest subtest score obtained in the CI sample. Therefore, not surprisingly, differences between the CI and NH samples on Word Definitions were no longer statistically significant after controlling for PPVT-4 scores. Processing and organizing challenging, linguistically complex information may be especially difficult for CI users because of disturbances in verbal WM and delays in fluent, speeded processing of language (Kronenberger et al., 2018; Pisoni et al., 2011).

Figure 4. Scatter plots of the association between "perfect-sentence" McGarr Speech Intelligibility scores and scaled scores on Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4) Formulated Sentences in Panel A. Scatter plots of the association between "perfect-sentence" McGarr Speech Intelligibility scores and scaled scores on CELF-4 Recalling Sentences in Panel B. CI = cochlear implant; NH = normal hearing.



Furthermore, syntactic processing seems to be a primary weakness for CI users, given the particularly low scores on the Formulated Sentences and Recalling Sentences subtests. It may be that these tests were the most linguistically complex in this study, and other higher order measures would show similar deficits. Mastery of syntactic processing, which requires processing of multiple words simultaneously with understanding the principles involved in the structure of language, may be more selectively affected in CI users because understanding and processing complex language requires extensive exposure to and practice with language, both of which are limited by early deafness and degraded auditory input from a CI. Thus, experiential factors could be one important source of weakness in syntactic processing. In addition, delays in verbal WM, which are found widely in CI users, may limit the capacity for holding language in mind in order to engage in syntactic processing. There is a need to further investigate a broader set of higher order language subtests in order to more clearly delineate the domains of language that are most at risk in CI users.

In making comparisons of higher order language performance in CI and NH samples, it is important to go beyond reporting summary group scores (such as means) and to examine the distribution of individual scores in each group, given the very large individual differences in spoken language outcomes routinely observed in the CI population. Analyses of score distributions can reveal patterns of risk and variability, particularly for individuals experiencing suboptimal outcomes. Examination of the distribution of CELF-4 scores in the CI and NH samples showed that about 50% of the CI sample fell in a score range with a distribution similar to the NH sample on the most challenging and complex CELF-4 subtests in this study (Formulated Sentences and Recalling Sentences). In contrast, about 50% of the CI sample scored in a positively skewed distribution well below that of the NH sample, including about 11% of the CI sample who scored at the floor. These large individual differences suggest that several additional cognitive factors operating within the CI group may be responsible for variability in higher order language scores, producing two distributions of outcome—optimal outcomes (consistent with those of NH peers) and suboptimal/at-risk outcomes (significantly delayed relative to NH peers). Identifying the factors responsible for this variability in higher order language scores offers the potential to better explain and impact language outcomes with novel interventions that are specifically targeted at weaknesses and delays in the underlying information-processing operations.

Results of analyses designed to better understand the variability in higher order language outcomes in CI users compared to NH peers showed unexpectedly that basic vocabulary (PPVT-4) was much more strongly related to higher order language outcomes in CI users than in NH peers. These differences were particularly pronounced for the Formulated Sentences and Recalling Sentences subtests, which were identified earlier as being highly influenced by comprehension, organization, integration, and memory skills and at a greater risk for delays in CI users. Vocabulary knowledge may have played a greater role in higher order language skills for CI users because stronger vocabulary allows for more efficient and effective organization, comprehension, and memory during language processing in individuals who need compensatory efforts to address less fluent, underspecified phonological and lexical representations of words in LTM. Alternatively, CI users may need to activate more effortful, organized executive processing in order to answer basic vocabulary questions on the PPVT-4 compared to their NH peers, for whom a single-word receptive vocabulary test requires less effort and executive processing; as a result, the PPVT-4 and CELF-4 Formulated Sentences and Recalling Sentences subtests may share greater variance in the CI sample as a result of overlapping demands on effort and executive control on those tests for CI users, which are largely absent for NH peers. In contrast, there were no statistically significant differences between CI and NH samples in correlations between PPVT-4 and the CELF-4 Word Classes and Word Definitions scores (based on z test of significance of difference between correlations), possibly because the latter subtests have more overlap with verbal knowledge in both the CI and NH samples.

Finally, as expected, Nonword Repetition, McGarr durations, and McGarr intelligibility scores were significantly correlated with almost all CELF-4 subtests in the CI sample, demonstrating the critical role of fast, automatic processing for higher order language processing in CI users. Correlations showing a stronger association in the CI sample (compared to the NH sample) between Nonword Repetition and only the Formulated Sentences and Recalling Sentences subtests also indicate that fast, fluent phonological coding skills play an important role particularly for complex higher order language processing involving the organization, integration, and coordination of linguistically complex information. Significant correlations between the McGarr scores and the CELF-4 Recalling Sentences scores may have been affected by the fact that both measures involve repetition of spoken sentences. However, there are also substantial differences between the tests. McGarr sentences are much shorter and less linguistically complex than CELF-4 Recalling Sentences. In addition, participants are provided with printed versions of the sentences in the McGarr task, whereas CELF-4 Recalling Sentences are recalled entirely from memory. Given these differences between sentence complexity and stimuli, the strong association observed between McGarr and CELF-4 Recalling Sentences scores in the CI group is impressive and is consistent with the hypothesis that fast, automatic language processing (reflected by McGarr scores) supports higher order language processing (reflected by CELF-4 Recalling Sentences).

Scatter plots further suggested the presence of two types of nonlinear associations between the fast, automatic channel (reflected by rapid phonological coding, verbal rehearsal speed, and speech intelligibility) and complex higher order language processing. The first type (see Figure 2) involved a score cutoff for Nonword Repetition that was sufficient but not necessary for good performance on the CELF-4 Formulated Sentences (and, to a less consistent extent, Recalling Sentences) subtest. Scores above a Nonword Repetition score of 60% were almost always associated with ("sufficient" for) average or better scores on the Formulated Sentences subtest, but scores below the cutoff of 60% were not consistently associated with ("not necessary" for) scores on the Formulated Sentences or Recalling Sentences subtest. Importantly, the 60% Nonword Repetition score also predicted high-variability sentence recognition in long-term CI users in another study (Smith et al., 2019), suggesting that this level of rapid phonological coding strongly supports both basic speech recognition and higher order language processing in CI users.

The other type of nonlinear association (e.g., a McGarr duration score of 2 s or greater or a McGarr intelligibility score of 60% or lower in Figures 3 and 4) involved a score cutoff that was necessary but not sufficient for good performance on the Formulated Sentences and Recalling Sentences subtests. Specifically, stronger scores on the McGarr measures were required ("necessary") in order for Formulated Sentences and Recalling Sentences to be at or above average, but many participants with stronger scores also had below-average Formulated Sentences and Recalling Sentences scores (not "sufficient"). In contrast, poor McGarr scores below the cutoffs (reflecting slow verbal rehearsal speed and poor speech intelligibility) were almost always associated with weaker language skills. Furthermore, it is notable that all NH participants had McGarr 7-Syllable Duration scores < 2 s and speech intelligibility scores > 60%, while CI users were distributed on both sides of these cutoffs. Hence, all NH participants fell in ranges of verbal rehearsal speed and speech intelligibility necessary but not sufficient for strong language skills, while only a subset of high-functioning CI users attained that level.

The finding of "necessary but not sufficient" inflection points for McGarr duration and intelligibility values predicting higher order language raises a question about what else is important for higher order language success for CI users who score above the McGarr inflection points. Based on the "sufficient but not necessary" inflection point for rapid phonological processing (nonword repetition), it is likely that rapid, efficient phonological processing may also be important for CI users who score in positive ranges for McGarr duration and intelligibility. Better phonological processing may help CI users to more efficiently build not only phonological representations of spoken words but also more complex syntactic representations of sentences, contributing to stronger, higher order language processing. Further research should be directed to better understanding the processes contributing to these inflection point curves and values.

Findings of strong relations between fast, automatic information-processing and higher order language skills in CI users are consistent with models (Ease of Language Understanding: Rönnberg et al., 2013; Framework for Understanding Effortful Listening: Pichora-Fuller et al., 2016; Auditory Neurocognitive Model: Kronenberger & Pisoni, 2018) that emphasize the importance of variability in fast, automatic processing for explaining individual differences in language skills in CI users compared to NH peers. Fast, automatic information processing may be more important in explaining variability in language outcomes in CI users than in NH peers for several reasons: First, CI users show more variability in fast, automatic processing than NH peers, particularly below an important inflection point at which information-processing speed significantly detracts from the quality of spoken language processing (Smith et al., 2019). Second, because of an early history of auditory deprivation followed by exposure to the degraded input of a CI, CI users are more likely to have underspecified, coarse-coded, comprised phonological and lexical representations of words in LTM (Kronenberger et al., 2018), interfering with fluent, fast, efficient processing of words in speech recognition and language comprehension. Therefore, faster, more fluent processing of language provides compensatory benefits to CI users and also indicates the likelihood that linguistic representations are well specified in the lexicon. Finally, faster speed of information processing allows for greater throughput, placing less strain on WM, which is at risk in CI users compared to NH peers (Kronenberger & Pisoni, 2018).

Although the current article focused on associations between fast, automatic language processing and complex higher order language skills, prior research has also demonstrated close links between the slow, effortful processing channel (reflected by executive functioning) and complex higher order speech and language outcomes in CI users (e.g. Beer et al., 2011; Kronenberger et al., 2014; Rönnberg et al., 2013). For example, Beer et al. (2011) found that WM, as measured by a parent report behavior checklist, is associated with CELF-4 Core Language scores. In addition, Kronenberger et al. (2014) found that verbal WM and fluency–speed correlated with CELF-4 Core Language scores, and Pisoni et al. (2011) found that WM is associated with vocabulary knowledge and core language scores on the CELF-4. Additional research investigating the influences of WM and other subdomains on complex higher order language skills is recommended based on these promising early results. However, the current study is the first to show consistent associations between multiple measures of the fast, automatic linguistic processing channel and complex higher order speech and language outcomes in CI users.

The results of this study should be interpreted in the context of limitations of the study design. First, the measure of rapid phonological coding was obtained 2 years after the other measures used in this study. As a result, changes over time may have attenuated the strength of some of the associations with rapid phonological coding, although nonword repetition performance is very stable over time (Casserly & Pisoni, 2013). Second, although the sample size for this study is large in comparison to most studies with CI users, our sample size is powered to detect medium effect sizes, not small effect sizes that may have been present. Third, the correlational design of this study does not allow for causal conclusions to be drawn; nevertheless, study findings are consistent with existing theory and empirical research concerning the role of higher order language processing and fast, automatic processing of language in CI users. Fourth, the sample had a wide age range across different stages of language development. Although no significant correlations were found between age and language scores, further investigation of age effects in higher order language processing is recommended.

An additional consideration in the interpretation of study results is the set of CELF-4 subtests investigated in this study. Although the six CELF-4 Core Language subtests used in this study assess complex higher order language processing, other CELF-4 subtests (and other measures of higher order language skills) may provide additional information about complex higher order language processing in CI users. Relatedly, the current study results are based on a small number of measures of fast, automatic information processing, and there is a need to further investigate associations with higher order language using other measures of fast, automatic processing. For example, for nonword repetition in the current study, accurate repetition of the entire word was used as the measure of rapid phonological coding. An alternative scoring method would be to code accuracy of phonemes as opposed to whole words.

An important influence on study results is the audibility of the test signals. Most of the tasks in this study required some auditory processing, which could be more challenging for CI users than NH peers and could therefore affect performance. We implemented several strategies to reduce the effects of audibility: First, all tests were administered by highly experienced speech-language pathologists in a quiet room with the examiner in clear view of the child. Second, for the McGarr task, subjects were provided with printed sentences. Third, when allowed according to directions, examiners could repeat instructions or items. Nevertheless, several measures (e.g., nonword repetition, some CELF-4 subtests) do not allow for repetition. Hence, audibility of stimuli and individual differences in auditory performance may have influenced results and are limitations of this study. Future research should systematically address these factors by controlling for audibility of stimuli (e.g., using visual stimuli) and testing differences in hearing history and performance on basic speech and hearing tests.

Findings from this study have several important clinical and translational implications. Routine assessment of spoken language outcomes in CI users should also include tests of higher order language processing (including comprehension and expression, understanding conceptual information, following directions, and completing tasks that require organization, integration, and coordination of information), in addition to tests of more basic language knowledge such as vocabulary and repetition of words and short sentences, because CI users may struggle with complex higher order language tasks even when their vocabulary knowledge and speech recognition skills are in the range of their NH peers. The importance of fast, automatic processing to support complex higher order language processing in CI users suggests that, in addition to interventions directly targeting higher order language processing, interventions to improve fast, automatic information processing could have positive indirect downstream effects on higher order language functioning in CI users. Our findings further demonstrate some specific areas of complex higher order language processing (Formulated Sentences and Recalling Sentences) that may be at the greatest risk for delay and that should be targeted by these novel interventions. Future research should investigate additional higher order language processing tasks such as understanding long passages of fluent speech, reading comprehension, and following verbal directions and instructions to achieve a goal or carry out a specific task.

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References

Beer, J., Kronenberger, W. G., & Pisoni, D. B. (2011). Executive function in everyday life: Implications for young cochlear implant users. *Cochlear Implants International, 12*(Suppl. 1), S89–S91. https://doi.org/10.1179/146701011X13001035752570

Casserly, E. D., & Pisoni, D. B. (2013). Nonword repetition as a predictor of long-term speech and language skills in children with cochlear implants. *Otology & Neurotology, 34*(3), 460–470. https://doi.org/10.1097/MAO.0b013e3182868340

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4)*. Minneapolis, MN: Pearson Assessments.

Freeman, V., & Pisoni, D. B. (2017). Speech rate, rate-matching, and intelligibility in early-implanted cochlear implant users. *The Journal of the Acoustical Society of America, 142*(2), 1043–1054. https://doi.org/10.1121/1.4998590

Freeman, V., Pisoni, D. B., Kronenberger, W. G., & Castellanos, I. (2017). Speech intelligibility and psychosocial functioning in deaf children and teens with cochlear implants. *Journal of Deaf Studies and Deaf Education, 22*(3), 278–289. https://doi.org/10.1093/deafed/enx001

Gathercole, S. E., & Baddeley, A. D. (1996). *The Children's Test of Nonword Repetition*. London, United Kingdom: The Psychological Corporation.

Geers, A. E., & Brenner, C. (2003). Background and educational characteristics of prelingually deaf children implanted by five years of age. *Ear and Hearing, 24*(Suppl. 1), 2S–14S. https://doi.org/10.1097/01.AUD.0000051685.19171.BD

Geers, A. E., Moog, J. S., Biedenstein, J., Brenner, C., & Hayes, H. (2009). Spoken language scores of children using cochlear implants compared to hearing age-mates at school entry. *Journal of Deaf Studies and Deaf Education, 14*(3), 371–385. https://doi.org/10.1093/deafed/enn046

Geers, A. E., Nicholas, J. G., & Sedey, A. L. (2003). Language skills of children with early cochlear implantation. *Ear and Hearing, 24*(Suppl. 1), 46S–58S. https://doi.org/10.1097/01.aud.0000051689.57380.1b

Geers, A. E., & Sedey, A. L. (2011). Language and verbal reasoning skills in adolescents with 10 or more years of cochlear

implant experience. *Ear and Hearing, 32*(Suppl. 1), 39S–48S. https://doi.org/10.1097/AUD.0b013e3181fa41dc
Hulme, C., Thomson, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. *Journal of Experimental Child Psychology, 38*(2), 241–253. https://doi.org/10.1016/0022-0965(84)90124-3
Kronenberger, W. G., Colson, B. G., Henning, S. C., & Pisoni, D. B. (2014). Executive functioning and speech-language skills following long-term use of cochlear implants. *Journal of Deaf Studies and Deaf Education, 19*(4), 456–470. https://doi.org/10.1093/deafed/enu011
Kronenberger, W. G., Henning, S. C., Ditmars, A. M., & Pisoni, D. B. (2018). Language processing fluency and verbal working memory in prelingually deaf long-term cochlear implant users: A pilot study. *Cochlear Implants International, 19,* 312–323. https://doi.org/10.1080/14670100.2018.1493970
Kronenberger, W. G., & Pisoni, D. B. (2018). Neurocognitive functioning in deaf children with cochlear implants. In H. Knoors & M. Marschark (Eds.), *Evidence-based practices in deaf education* (pp. 363–396). New York, NY: Oxford University Press.
Kronenberger, W. G., Pisoni, D. B., Henning, S. C., & Colson, B. G. (2013). Executive functioning skills in long-term users of cochlear implants: A case control study. *Journal of Pediatric Psychology, 38*(8), 902–914. https://doi.org/10.1093/jpepsy/jst034
Language and Reading Research Consortium. (2015). The dimensionality of language ability in young children. *Child Development, 86*(6), 1948–1965. https://doi.org/10.1111/cdev.12450
McGarr, N. S. (1981). The effect of context on the intelligibility of hearing and deaf children's speech. *Language and Speech, 24*(3), 255–264. https://doi.org/10.1177/002383098102400305
Montag, J. L., AuBuchon, A. M., Pisoni, D. B., & Kronenberger, W. G. (2014). Speech intelligibility in deaf children after long-term cochlear implant use. *Journal of Speech, Language, and Hearing Research, 57,* 2332–2343. https://doi.org/10.1044/2014_JSLHR-H-14-0190
Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N.-Y., Quittner, A. L., . . . CDaCI Investigative Team. (2010). Spoken language development in children following cochlear implantation. *JAMA: Journal of the American Medical Association, 303*(15), 1498–1506. https://doi.org/10.1001/jama.2010.451
Nittrouer, S., Caldwell-Tarr, A., Sansom, E., Twersky, J., & Lowenstein, J. H. (2014). Nonword repetition in children with cochlear implants: A potential clinical marker of poor language acquisition. *American Journal of Speech-Language Pathology, 23*(4), 679–695. https://doi.org/10.1044/2014_AJSLP-14-0040
Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., . . . Wingfield, A. (2016). Hearing impairment and cognitive energy: The Framework for Understanding Effortful Listening (FUEL). *Ear and Hearing, 37*(Suppl. 1), 5S–27S. https://doi.org/10.1097/aud.0000000000000312
Pisoni, D. B., & Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear and Hearing, 24*(Suppl. 1), 106S–120S.
Pisoni, D. B., Cleary, M., Geers, A. E., & Tobey, E. A. (1999). Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: New process measures of performance. *The Volta Review, 101*(3), 111–164.
Pisoni, D. B., Kronenberger, W. G., Harris, M. S., & Moberly, A. C. (2018). Three challenges for future research on cochlear implants. *World Journal of Otorhinolaryngology—Head and Neck Surgery, 3*(4), 240–254. https://doi.org/10.1016/j.wjorl.2017.12.010
Pisoni, D. B., Kronenberger, W. G., Roman, A. S., & Geers, A. E. (2011). Measures of digit span and verbal rehearsal speed in deaf children after more than 10 years of cochlear implantation. *Ear and Hearing, 32*(Suppl. 1), 60S–74S. https://doi.org/10.1097/AUD.0b013e3181ffd58e
Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., . . . Rudner, M. (2013). The Ease of Language Understanding (ELU) model: Theoretical, empirical, and clinical advances. *Frontiers in Systems Neuroscience, 7,* 31. https://doi.org/10.3389/fnsys.2013.00031
Ruffin, C. V., Kronenberger, W. G., Colson, B. G., Henning, S. C., & Pisoni, D. B. (2013). Long-term speech and language outcomes in prelingually deaf children, adolescents and young adults who received cochlear implants in childhood. *Audiology & Neuro-Otology, 18*(5), 289–296. https://doi.org/10.1159/000353405
Semel, E., Wiig, E. H., & Secord, W. A. (2003). *Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4)*. Minneapolis, MN: Pearson Assessments.
Smith, G. N. L., Pisoni, D. B., & Kronenberger, W. G. (2019). High-variability sentence recognition in long-term cochlear implant users: Associations with rapid phonological coding and executive functioning. *Ear and Hearing, 40,* 1149–1161. https://doi.org/10.1097/AUD.0000000000000691
Spaulding, T. J., Plante, E., & Farinella, K. A. (2006). Eligibility criteria for language impairment: Is the low end of normal always appropriate. *Language, Speech, and Hearing Services in Schools, 37*(1), 61–72. https://doi.org/10.1044/0161-1461(2006/007)
Tomblin, J. B., Spencer, L. J., & Gantz, B. J. (2000). Language and reading acquisition in children with and without cochlear implants. *Advances in Oto-Rhino-Laryngology, 57,* 300–304. https://doi.org/10.1159/000059145
Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence*. New York, NY: The Psychological Corporation.