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Research Article

Verbal Processing Speed and Executive Functioning in Long-Term Cochlear Implant Users

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Purpose: The purpose of this study was to report how *verbal rehearsal speed* (VRS), a form of covert speech used to maintain verbal information in working memory, and another verbal processing speed measure, perceptual encoding speed, are related to 3 domains of executive function (EF) at risk in cochlear implant (CI) users: verbal working memory, fluency-speed, and inhibition-concentration.

Method: EF, speech perception, and language outcome measures were obtained from 55 prelingually deaf, long-term CI users and matched controls with normal hearing (NH controls). Correlational analyses were used to assess relations between VRS (articulation rate), perceptual encoding speed (digit and color naming), and the outcomes in each sample.

Results: CI users displayed slower verbal processing speeds than NH controls. Verbal rehearsal speed was related to 2 EF domains in the NH sample but was unrelated to EF outcomes in CI users. Perceptual encoding speed was related to all EF domains in both groups.

Conclusions: Verbal rehearsal speed may be less influential for EF quality in CI users than for NH controls, whereas rapid automatized labeling skills and EF are closely related in both groups. CI users may develop processing strategies in EF tasks that differ from the covert speech strategies routinely employed by NH individuals.

The electrical stimulation provided by a cochlear implant (CI) has provided many severe-to-profoundly deaf children with sufficient sensory information to support speech perception and the development of spoken language skills (Geers, Brenner, & Tobey, 2011; Niparko et al., 2010; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). For children implanted at young ages, expressive and receptive language scores measured in the quiet are often within a standard deviation of the scores obtained for children with normal hearing (NH children) (Geers & Sedey, 2011). Despite these reported successes, young deaf children who have received CIs display more variability in speech and language outcomes than NH children, and some CI users continue to struggle with speech, language, and verbal processes into adulthood (Geers & Sedey, 2011).

Several researchers have proposed that the unexplained variability in speech and language outcomes observed in CI users stems in part from individual differences in core neurocognitive information processing mechanisms, such as sequential processing and verbal working memory (e.g., Conway, Pisoni, Ananya, Karpicke, & Henning, 2011; Geers, Strube, Tobey, Pisoni, & Moog, 2011; Marschark, Rhoten, & Fabich, 2007). Reciprocally, there is also strong evidence that long-term linguistic knowledge feeds back to support real-time performance during verbal working memory tasks (e.g., Cowan, Rouder, Blume, & Saults, 2012; Gathercole & Adams, 1994; Morey, Morey, van der Reijden, & Holweg, 2013). Thus, an early period of sensory deprivation, such as prelingual deafness, followed by the subsequent use of a CI may have downstream effects on other areas of neurocognitive functioning that are partially dependent on auditory experience and language processing activities for their development (Geers & Moog, 1987; Luria, 1973).

One such area that has been found to be at risk in CI users is executive functioning (Kronenberger, Pisoni, Henning, & Colson, 2013). Although there is no universally agreed-upon definition of executive function (EF), most conceptualizations describe EF as a class of cognitive skills that are used to plan, guide, and regulate behavior over time (Anderson, 2002; Best, Miller, & Jones, 2009; Gioia, Isquith, Guy, & Kenworthy, 2000; Hart, Schwartz, & Mayer; 1999; Shute

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& Huertas, 1990). Extensive research has identified verbal working memory as one of the core components of the EF system (Best et al., 2009; Gioia et al., 2000; Hart et al., 1999; Shute & Huertas, 1990); other EF skills include control processes such as inhibition-concentration, fluency-speed during completion of complex tasks, task switching, planning, goal maintenance, organization, and nonverbal working memory (Anderson, 2002; Best et al., 2009; Gioia et al., 2000; Miyake et al., 2000; Shute & Huertas, 1990). The broad heterogeneous nature of EF has made it difficult to articulate a cohesive structure that identifies all possible EF components and specifies a complete theory encompassing the entire range of cognitive skills (Barkley, 2012), especially because EF, and disruptions to the EF system, can be conceptualized on a number of different levels of information processing.

One useful conceptualization is to view EF as a set of latent cognitive skills. Each skill can be tapped by multiple lab-based or real-world activities, and each of those activities often require the use and coordination of many EF skills for successful completion. A common taxonomy from Miyake and colleagues (2000) describes three basic EFs: (a) maintaining and updating goal-relevant information ("updating"), (b) inhibiting proponent responses ("inhibition"), and (c) rapid and efficient switching between mental concepts or tasks ("shifting"), although variations on this taxonomy have been proposed by other theorists. For example, "updating" is commonly subsumed within the broader context of "working memory operations" (Cepeda, Blackwell, & Munakata, 2013; Hofmann, Schmeichel, & Baddeley, 2012).

EF Skills in CI Users

Delays and disturbances in the EF system have been observed in children with CIs at multiple levels. For example, Beer, Pisoni, Kronenberger, and Geers (2010) asked parents of CI users to complete—on their child's behalf—an EF behavior checklist (Behavior Rating Inventory of Executive Function [BRIEF]) that assesses self-regulation during everyday, real-world behaviors. Based on these parental reports, children with CIs were more likely than NH children to display executive dysfunction in shifting, emotional control, initiation, working memory, planning and organization, and organization of materials (Beer et al., 2010). Even very young CI users (ages 3–6) were reported to have elevated (i.e., dysfunctional) scores relative to age-matched NH controls on the Inhibitory Control and Working Memory subscales of the BRIEF (Beer, Kronenberger, Castellanos, Colson, Henning, & Pisoni, 2014). A more recent study found that CI users were at two to five times the risk of clinically significant problems with EF, compared to a matched NH control sample (Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014).

CI and hearing aid users also display executive function deficits on many—but not all—traditional laboratory-based performance measures (Figueras, Edwards, & Langdon, 2008; Kronenberger et al., 2013). Figueras et al. (2008) found that both CI and hearing aid users performed worse than NH controls on measures tapping inhibition and working memory, shifting, and verbal creativity but not on a measure of spatial creativity. Kronenberger et al. (2013) reported that long-term CI users also perform more poorly than a sample of age- and IQ-matched NH controls on several lab-based EF behavioral measures that could be classified into three basic domains: (a) verbal working memory, (b) fluency-speed, and (c) inhibition-concentration. Consistent with the findings by Figueras and colleagues (2008), the two groups tested by Kronenberger et al. (2013) did not differ on an EF skill unlikely to receive support from long-term linguistic knowledge: visuospatial working memory. Importantly, all but two of the EF tasks (forward digit span and backward digit span) administered by Kronenberger et al. (2013) were presented visually, and most required a manual response. Thus, the EF differences observed between CI and NH listeners could not be attributed to differences in audibility or speech production in the sample of CI users.

EF skills have been linked to cognitive control and self-regulation of many real-world, everyday behaviors such as paying attention during class, dealing with stressful situations, resisting unhealthy food options, and smoking cessation (Hofmann et al., 2012). An intact EF system is also necessary to direct and regulate other mental processes, including language and reading comprehension (Barkley, 2012; Norman & Shallice, 1986). Because EF skills are critical for quality of life and speech-language outcomes, EF deficits in CI users pose potential risks for adjustment and development beyond speech and hearing skills. Although considerable variation in EF skills exists within the CI population, little is currently known about the underlying factors that contribute to the risk of poor EF in this clinical population. Knowledge about the factors that contribute to EF deficits in the CI population would fill in a critical gap in the research, enhance our understanding of how EF develops, and suggest novel methods for early identification and intervention. Additionally, investigating individual differences in EF skills may help us to understand the large unexplained variance in speech and language outcomes in CI samples (Niparko et al., 2010).

Verbal Processing Speed, Executive Functioning, and Spoken Language

Some preliminary research has investigated potential underlying contributors to functioning in one EF area, verbal working memory, in children with CIs (Pisoni, Kronenberger, Roman, & Geers, 2011). Working memory, the limited amount of information that can be temporarily maintained in an accessible state for current or future information processing, contributes to variability on a range of complex skills. Individual differences in working memory capacity contribute to the variance on measures of reading comprehension (Daneman & Carpenter, 1980) as well as general intelligence and academic achievement (Engle, Tuholski, Laughlin, & Conway, 1999). Given that working memory is a central processing component of regulation and control of a number of complex neurocognitive abilities and real-life skills, it is not surprising that both verbal and nonverbal working

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memory[1] are often included as components of the larger EF system (Barkley, 2012; Cepeda et al., 2013; Hofmann et al., 2012).

The speed of covert mental information processing operations, particularly covert verbal rehearsal, or the silent repetition of to-be-remembered items (Hulme, Thomson, Muis, & Lawrence, 1984; Hulme & Tordoff, 1989; Jarrold & Tam, 2011), and perceptual encoding speed (Case, Kurland, & Goldberg, 1982) are closely related to verbal working memory capacity in typically developing NH children. Using covert verbal rehearsal, phonological memory traces can be quickly cycled in and out of the working memory store before those traces decay. The faster items can be rehearsed, the less likely those items are to decay before needing to be retrieved for recall (Broadbent, 1975; Cowan, 2001). Verbal rehearsal speed (VRS) is routinely estimated using some measure of articulation rate, and the strength of the correlation between VRS and simple memory span tasks, such as forward digit span, is taken to reflect the efficiency of covert verbal rehearsal processes (Baddeley, Thompson, & Buchanan, 1975; Hulme et al., 1984). Using articulation rate as a proxy for VRS is also supported by neurophysiological research showing that VRS recruits the same anterior brain regions involved in overt speech planning and execution (Awh, Jonides, Smith, Schumacher, Koeppe, & Katz, 1996). VRS is related to the variability in verbal working memory observed across age groups (Hulme et al., 1984; Hulme & Tordoff, 1989), stimulus materials (Baddeley et al., 1975), languages (Naveh-Benjamin & Ayers, 1986), and hearing status (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003).

Previous findings from our laboratory showed that young CI users have slower verbal rehearsal processes than their NH peers (Pisoni et al., 2011). Pisoni and Cleary (2003) investigated VRS as a possible factor underlying differences in verbal memory span between deaf children with CIs and NH children. In addition to having shorter forward and backward digit spans than their NH age-matched controls, CI users also displayed much slower and more variable articulation rates in a sentence repetition task, indicating atypical verbal rehearsal strategies (Pisoni & Cleary, 2003). Moreover, within the group of CI children, digit span scores were found to be strongly associated with VRS; children who displayed slower articulation rates also had shorter forward digit spans (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003). The relation between VRS and verbal working memory span observed in these deaf children is consistent with previous findings in NH children and adults (e.g., Baddeley et al., 1975; Hulme et al., 1984). It is also consistent with the proposal that, although rehearsal is often considered an automatic process that requires few processing resources, the efficiency of rehearsal processes throughout development—and into adulthood—relies heavily on experience with the stimuli to be rehearsed (Engle et al., 1999; Gathercole & Adams, 1994; Jarrold & Tam, 2011; Morey et al., 2013).

Morey and colleagues (2013) proposed that the extensive linguistic experience of typically developing NH adults supports highly efficient, automatized covert verbal rehearsal processes that, once initiated, can continue with very little attentional resources. In contrast, nonverbal/visual–spatial rehearsal processes are often resource demanding well into adulthood (Logie, 1995; Morey et al., 2013; Naveh-Benjamin & Jonides, 1984). However, both forms of rehearsal—verbal and visual–spatial—require active attentional resources to engage (Morey et al., 2013). Consequently, not all adults appear to engage covert verbal rehearsal processes equally (Turley-Ames & Whitfield, 2003). These findings suggest that although covert verbal rehearsal is often considered to occur automatically, it may be better characterized as an optionally employed maintenance strategy with varying degrees of efficiency.

Verbal working memory is significantly associated with speech perception (Cleary, Pisoni, & Kirk, 2000; Nittrouer, Caldwell-Tarr, & Lowenstein, 2013), grammar (Willstedt-Svensson, Löfqvist, Almqvist, & Sahlén, 2004), vocabulary (Cleary et al., 2000; Geers, Pisoni, & Brenner, 2013; Nittrouer et al., 2013; Wass et al., 2008), reading (Geers et al., 2013), word learning (Willstedt-Svensson et al., 2004), and conversational communication (Ibertsson, Hansson, Asker-Arnason, Sahlén, & Mäki-Torkko, 2009; Lyxell et al., 2008) in CI users. Because of the foundational role that VRS plays in verbal working memory, VRS is therefore a likely contributor to long-term outcomes in speech and language skills in CI users and may explain the relation between verbal working memory and long-term spoken language outcomes. For example, Pisoni and Cleary (2003) reported that digit span scores correlated with speech and language measures, but this relationship could be attributed to their shared variance with VRS. Furthermore, measures of verbal rehearsal speed obtained during elementary school reliably predicted speech and language outcomes measured more than 10 years later (Pisoni et al., 2011).

Another measure of fluency and speed of verbal processing is perceptual encoding speed. Perceptual encoding speed is one type of domain-general cognitive processing speed that specifically involves the rapid search of long-term memory and production of a verbal label that matches a test stimulus, such as the time taken to recognize a spoken word, name a color, or repeat a digit. Measures of perceptual encoding speed, such as rapid automatized naming tasks, are correlated with performance in a number of EF domains in NH children, reflecting the efficiency of verbal processing—though potentially constrained by a more general processing speed mechanism—in response to task demands (Case

[1]We make no claims as to the domain specificity or generality of the working memory system(s). Although a popular model of working memory assumes distinct systems for verbal and nonverbal materials (Baddeley & Hitch, 1974), other models of working memory suggest that modality differences emerge because long-term knowledge makes processing within working memory more efficient (e.g., Cowan, 2001). Here, we make the distinction between *verbal working memory* and *nonverbal working memory* to highlight the nature of the stimulus materials (i.e., phonological or visual–spatial) because our interest is specifically in language-mediated strategies, such as covert verbal rehearsal, and the role that linguistic experience plays in the efficiency of those strategies in tasks with verbal materials.

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et al., 1982; Cepeda et al., 2013; Christopher et al., 2012). In turn, verbal processing—in the form of self-directed covert speech—can be a critical tool in EF implementation (Barkley, 2012). Perceptual encoding and covert verbal rehearsal differ in that perceptual encoding is an obligatory and necessary process, whereas VRS and other forms of self-directed covert speech are optionally employed; thus, these two processes may differentially contribute to the large individual differences in speech, language, and EF outcomes observed in CI users.

Research Questions and Hypotheses

In this report, we sought to evaluate differences in verbal processing speed between CI users and NH peers and to investigate relations between VRS, perceptual encoding speed, and executive functions. We focused on the three EF components recently identified by Kronenberger et al. (2013) as being at risk in children with CIs: verbal working memory, fluency-speed, and inhibition-concentration. Based on earlier findings, we expected children with CIs to show significantly slower VRS than the NH sample (Prediction 1), and we expected VRS to be strongly related to speech and language skills in the CI sample (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2013). NH children were expected to use self-directed speech for a broad variety of EF activities (Barkley, 2012), resulting in robust correlations of VRS with the three EF domains in the NH sample (Prediction 2). However, the role of self-directed speech in executive functioning of deaf children with CIs is less clear. To the extent that the CI sample utilized self-directed covert speech during executive functioning, they should also show relations between VRS and EF measures (Prediction 3). However, if the disruptions to EF previously observed in these children by Kronenberger et al. (2013) arise from their failure to efficiently utilize language mediation as a behavioral control strategy, as suggested by Figueras et al. (2008), VRS and EF would not be correlated.

For perceptual encoding speed, based on earlier research using children with dyslexia (Wolf et al., 2000), poor reading comprehension (Christopher et al., 2012), and attention deficit/hyperactivity disorder (Tannock, Martinussen, & Frijters, 2000), we predicted that prelingually deaf, long-term CI users, many of whom also have poor language, reading, and EF skills, would show slower and less efficient perceptual encoding operations than NH controls (Prediction 4). Finally, we examined the relations between perceptual encoding speed and speech, language, and EF outcomes in long-term CI users compared to NH controls. From the developmental literature on children with language delays and EF disorders, we predicted that perceptual encoding speed would be strongly related to the EF tasks in both NH and CI samples (Prediction 5).

Method

Participants

CI sample. The sample of CI users consisted of 55 children, adolescents, and young adults who met the following five inclusion criteria: (a) onset of severe-to-profound hearing loss (>70 dB hearing loss in the better hearing ear) prior to age 3 years; (b) cochlear implantation prior to age 7 years; (c) at least 7 years of CI use at the time of testing; (d) consistent use of a currently available, state-of-the-art multichannel CI system; and (e) living in a home where English is the primary language. Potential CI participants were excluded if (a) a comorbid developmental or neurocognitive delay or disability other than hearing loss was indicated by the medical chart or parental report or (b) their nonverbal IQ score was greater than 1 standard deviation below the normative mean.

NH control sample. The NH control sample consisted of 55 children, adolescents, and young adults who met the following inclusion criteria (a) ages 7–25 years, (b) had a nonverbal IQ score within 1 standard deviation of the norm mean or higher, (c) passed a basic audiometric hearing screening assessment (each ear was tested individually with headphones at frequencies of 500, 1000, 2000, and 4000 Hz at 20 dB), (d) reported no significant developmental or cognitive delays, and (e) matched 1:1 with the CI sample on nonverbal IQ (±1 standard deviation) and age (±2 years for participants younger than 20 years; ±2.5 years for participants older than 20 years).

Recruitment. CI participants were recruited through multiple venues, including the patient populations receiving clinical services at a large hospital-based CI clinic and CI users who had participated in previous studies in our research center. The study was also advertised to local professionals and schools who had contact with CI users. NH participants were recruited from the community using flyers posted in the same institutions and geographic areas from which the CI sample was recruited. E-mail and internet sites affiliated with our CI clinic and university were also used for recruitment of NH participants.

Procedure

Prior to testing, participants were fully consented (with assent by children as appropriate) to the protocol approved by the university institutional review board. All testing was completed at a hospital-based clinic. All CI users were tested by licensed speech-language pathologists; NH participants were tested either by the same speech-language pathologists or by experienced psychometric technicians.

Both samples reported the following demographic variables: age at time of testing, sex, family income, and race/ethnicity. The CI sample also reported age at onset of deafness, age at time of implantation, and years of implant use. Additional variables recorded for the CI sample included communication mode and preimplant residual hearing (mean unaided pure-tone average in the better-hearing ear for the frequencies 500, 1000, and 2000 Hz at 20 dB).

Measures

VRS was estimated using overt articulation rate of meaningful sentences. For each of the 36 sentences in the

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McGarr Sentence Intelligibility Test (McGarr, 1981), the examiner said the target sentence aloud while showing participants a card with the printed sentence in order to reduce demands on phonological short-term memory. The participant was then prompted to repeat the sentence back to the examiner. The participant was instructed to reproduce the sentence accurately and was allowed to respond at a natural conversational pace. If the examiner judged the response as being inaccurate (i.e., the response contained a word omission, deletion, or substitution), she repeated the sentence and prompted for a second response attempt. Digital audio recordings were made of each participant's vocal responses. Sentence durations were measured individually by hand from the digital audio recordings using Praat (Boersma & Weenink, 2012). Using both auditory and visual cues from waveforms and speech spectrograms, two experienced coders marked the beginning and end of each utterance. Sentence durations, in seconds, were calculated using the mean duration of those seven-syllable McGarr sentences that were correctly reproduced on the first attempt. All responses of 50 CI and 22 NH participants were coded by both coders at a high rate of reliability (interclass correlation coefficient = .903 with a 95% confidence interval of 0.896 to 0.910).

Perceptual encoding speed was assessed using two speeded naming measures. Digit naming speed was calculated from the number of digits named during the Numeral Naming baseline control condition of the Counting Interference Task (Hummer et al., 2011). Participants rapidly name a series of randomly presented digits (1, 2, or 3) from a stimulus page for 45 seconds; scores are the number of digits read prior to the time limit. Color naming speed was calculated from the number of colors named in 45 seconds during the Color Naming baseline control condition of the Stroop Color and Word Test (Golden, Freshwater, & Golden, 2003). Participants rapidly name the colors of a series of XXXs (either red, green, or blue) from a stimulus page for 45 seconds.

Nonverbal intellectual ability was assessed using the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). This task measures visual–spatial and abstract reasoning skills by requiring participants to complete a pattern of geometric designs based on an underlying concept or rule.

Speech perception, language, and executive functioning composite scores. Composite scores for speech perception, language, and three major areas of executive functioning (verbal working memory, fluency-speed, and inhibition-concentration) were derived from a battery of multiple individual tests within each of these broad domains (see Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013, and Kronenberger et al., 2013, for a full description of the organization of the tests into the described domains). Principal components analysis of the individual measures within each broad domain supported a single component based on scree plots and the eigenvalue >1 convention (see online supplemental Tables 1–5). Additionally, intercorrelations of the tasks within each domain are provided in online supplemental Tables 6–10. Composite scores were created by z-transforming scores for each individual measure (based on the mean and standard deviation from the entire sample) and summing the z scores to give each participant a single composite score for that domain. A composite speech perception score was calculated only for the participants in the CI group. The NH group was not administered any of the speech perception measures because NH samples routinely score at ceiling on speech perception tasks obtained in quiet. Comparisons of executive functioning scores for the CI and NH samples (sample composition differs slightly from the samples in this article because of different inclusion and exclusion criteria) are reported in Kronenberger et al. (2013) for executive functioning measures. Kronenberger et al. (2013) found weaker EF performance in CI users for all three areas of executive functioning (verbal working memory, fluency-speed, and inhibition-concentration), compared to matched NH peers.

A speech perception composite score was created from the following five tasks, all presented at 65 dB SPL: (a) words correct on Hearing in Noise Sentences for Children (HINT-C) in quiet (Nilsson, Soli, & Gelnett, 1997) in which participants repeated meaningful spoken English sentences presented in a quiet background; (b) words correct on HINT-C in noise, with sentences presented in speech-shaped noise at +5 dB SNR; (c) mean Easy and Hard Word score for the Lexical Neighborhood Test (LNT; Kirk, Pisoni, & Osberger, 1995), which is used to assess open-set recognition of isolated spoken monosyllabic words in quiet. Participants repeated words from a 50-word list that contained lexically easy and lexically hard words. A single score was calculated from the mean of LNT Easy and LNT Hard; (d) mean Easy and Hard score for the auditory-only presentation of the Auditory-Visual Lexical Neighborhood Sentence Test (AVLNST; Holt, Kirk, Pisoni, Burckhartzmeyer, & Lin, 2005) in which participants repeated prerecorded, spoken sentences that contained three keywords that vary in lexical difficulty (Easy vs. Hard); and (e) mean Easy and Hard score for audiovisual presentation of the AVLNST, in which the participant saw a visual presentation of the speaker's face along with the auditorily presented sentence. Each AVLNST measure was scored using the mean percentage of key words correct for easy and hard sentences.

A language composite score was calculated from the standard scores of two norm-referenced language measures: (a) the Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007), a test of one-word receptive vocabulary in which the examiner says a word and the participant must point to one of four pictures that correctly depicts that word; and (b) the Clinical Evaluation of Language Fundamentals–Fourth Edition (Semel, Wiig, & Secord, 2003) Core Language score, which measures expressive and receptive language skills.

A verbal working memory composite score was calculated using raw scores obtained from the (a) Digit Span Forward and (b) Digit Span Backward subtests of the

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Wechsler Intelligence Scale for Children–Third Edition (Wechsler, 1991), as well as (c) the Visual Digit Span subtest of the Wechsler Intelligence Scale for Children–Fourth Edition–Integrated (WISC-IV-I; Wechsler et al., 2004). In Digit Span Forward and Digit Span Backward, participants reproduced a sequence of spoken digits in either forward or backward order. In Visual Digit Span, the digit sequences were visually presented, and the participant reproduced the sequences in forward order.

The inhibition-concentration composite score was calculated from raw scores for (a) the Color-Word condition of the Stroop Color and Word Test, a test of naming ink colors used to spell incongruent color words (Golden et al., 2003); (b) the Number-Letter Switching condition of the Trail-Making Test (switching between a series of numbers and letters to connect dot locations; Delis, Kaplan, & Kramer, 2001); (c) commission errors; (d) omission errors; and (e) Response Time Variability scores of the Test of Variables of Attention (a continuous performance test that requires participants to respond when a square is presented at the top of a screen while not responding to a square presented at the bottom of the screen; Leark, Dupuy, Greenberg, Corman, & Kindschi, 1996).

The fluency-speed composite score was calculated from raw scores for (a) the Coding subtest (a measure of ability to rapidly reproduce a sequence of visual symbols based on a corresponding sequence of numerals, with each numeral corresponding to a unique symbol) of the WISC-IV-I, (b) the Coding Copy subtest (which requires rapid reproduction of the visual symbols from the Coding subtest without the corresponding numerals) of the WISC-IV-I, (c) the Pair Cancellation subtest (rapid identification of pictures in a large stimulus array) of the Woodcock–Johnson Tests of Cognitive Abilities–Third Edition (WJ-III-Cog; Woodcock, McGrew, & Mather, 2001), (d) the Visual Matching subtest (which involves rapid identification of matching numbers within a visual array) of the WJ-III-Cog, and (e) the Retrieval Fluency subtest (which requires participants to rapidly retrieve and generate words from specific semantic categories in long-term memory) of the WJ-III-Cog.

Data Analysis Approach

Participant demographic characteristics, hearing history, and nonverbal intellectual ability are summarized in Table 1. Performance measures of verbal information processing speed (VRS, Digit Naming, and Color Naming) are summarized in Table 2; *t* tests or χ^2 tests were used to statistically assess significant differences between groups. Pearson correlations were then used to investigate relations between VRS (McGarr Sentence Duration) and perceptual encoding speed (Digit Naming and Color Naming) and speech perception, language, and the three EF domains (Table 3). Correlations were calculated separately for the CI and NH groups to investigate differences in the associations between these subsamples. Because of the large number of correlations, all reported *p* values for the primary analyses have been adjusted using a Benjamini-Hochberg correction (Benjamini & Hochberg, 1995). Finally, partial correlation analyses were conducted for each sample to assess the contributions of VRS and perceptual encoding

Table 1. Participant demographic characteristics.

Variable	CI *M* (*SD*)	NH *M* (*SD*)	CI and NH *t*
Age (years)	15.3 (4.9)	15.5 (5.0)	0.24
Income[a]	7.0 (2.5)	7.2 (2.6)	0.56
Wechsler Abbreviated Scale of Intelligence Matrix Reasoning T-score	56.3 (5.8)	56.5 (6.9)	0.28
Age at implant (months)	36.4 (20)		
Years of implant use	12.3 (3.9)		
Onset of deafness (months)	3.2 (8.2)		
Best pre-implant pure-tone average	108.7 (10.7)		
CMRS[b]	4.7 (0.9)		
Race/ethnicity	*N*	*N*	χ^2
White, non-Hispanic	48	39	6.00
Hispanic	2	2	
Black/African American	1	6	
Asian	1	3	
Mixed race	3	5	
Gender			
Male	29	23	1.31
Female	26	32	

Note. CI = cochlear implant users; NH = controls with normal hearing; CMRS = Communication Mode Rating Scale. Table includes means (and standard deviations) for demographic variables for CI users and NH controls (when appropriate), as well as measures of verbal rehearsal speed (VRS) and perceptual encoding speed for both groups. Also included are *t* tests and tests of χ^2 comparing CI and NH groups.

[a]Family income was reported on a 1 (<$5,500) to 10 (≥$95,000) scale; intermediate values of 3, 5, and 7 correspond to annual income values of $15,000–$24,999, $35,000–$49,999, and $65,000–$79,999, respectively. [b]Communication mode was coded on a 1 (*mostly sign*) to 6 (*auditory-verbal*) rating scale (see Geers & Brenner, 2003).

Table 2. Verbal rehearsal and perceptual encoding speed.

Variable	CI *M* (*SD*)	NH *M* (*SD*)	CI and NH *t*
VRS	1.9 (0.4)	1.6 (0.2)	4.6***
Digit Naming	83.5 (18.3)	100.8 (23.9)	4.2***
Color Naming	57.3 (12.6)	65.6 (15.1)	3.2**

Note. VRS = verbal rehearsal speed, which is the utterance duration of seven-syllable McGarr Sentences (McGarr Sentence Intelligibility Test; McGarr, 1981); Digit Naming = Counting Interference Task Numeral Naming score; Color Naming = Stroop Color Naming (Golden, Freshwater, & Golden, 2003). Table includes means (and standard deviations) for measures of VRS and perceptual encoding speed for both groups. Also included are *t* tests comparing CI and NH groups.

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

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Table 3. Correlations (and *p* values)[a] of VRS and perceptual encoding speed with speech, language, and executive function composites in CI and NH groups.

	VRS				Perceptual encoding speed			
	McGarr utterance duration				Composite			
	CI		NH		CI		NH	
Variable	Correlation	p	Correlation	p	Correlation	p	Correlation	p
Speech perception composite	–0.51	.00			.07	.61		
Language composite	–0.51	.00	–0.08	.75	.21	.12	.07	.75
Verbal working memory composite	–0.27	.11	–0.33	.04	.63	.00	.61	.00
Fluency-speed composite	–0.17	.40	–0.33	.04	.71	.00	.81	.00
Inhibition-concentration composite	0.05	.80	0.30	.08	–.68	.00	–.83	.00

[a]Benjamini-Hochberg adjusted *p* values.

speed to the three EF composite scores while controlling for chronological age.

Results

Comparisons of CI and NH Samples on Demographic Variables, VRS, and Perceptual Encoding Speed

The CI and NH samples did not differ in nonverbal IQ, age, family income, race, or gender (see Table 1). However, consistent with previous findings obtained with a different group of CI users, the long-term CI users in the present study produced the seven-syllable McGarr sentences more slowly than the NH controls (see Table 2). The CI users were also much more likely than the NH controls to make an error during their first attempt at reproducing the McGarr target utterance, $\chi^2(1, N = 110) = 54.0$, $p < 0.001$: 51 NH participants and only 13 CI users correctly reproduced all 12 seven-syllable McGarr target sentences on their first attempt. The CI sample produced fewer digits during the Digit Naming task and fewer colors during the Color Naming task than the NH sample (see Table 2).

Digit Naming and Color Naming were strongly correlated with each other in both groups ($r = .73$, $n = 55$, $p < .001$ for the CI sample and $r = .80$, $n = 55$, $p < .001$ for the NH sample). Because of the strong correlations between Digit Naming and Color Naming, the two measures were combined into a single composite score, calculated according to the same procedure that was described earlier for the composite scores for the three EF domains. Clinical administrations of multiple rapid automatized naming tasks are often similarly combined (e.g., Rapid Automatized Naming and Rapid Alternating Stimulus tests; Wolf & Denckla, 2005). Verbal rehearsal speed and the perceptual encoding speed composite were moderately correlated with each other in both groups ($r = -.32$, $n = 55$, $p < .05$ for the CI sample and $r = -.40$, $n = 55$, $p < .01$ for the NH sample). Correlations of VRS and perceptual encoding speed with participant demographic and hearing characteristics are reported in Table 4.

Correlations of VRS and Perceptual Encoding Speed With Speech and Language Measures for CI and NH Samples

Table 3 displays the correlations of VRS and perceptual encoding speed measures with the speech perception composite (CI group only) and language composite (for both the CI and NH groups). As in our previous work, VRS, as estimated by seven-syllable McGarr utterance length, was also found to be strongly correlated with the speech perception composite score in this group of long-term CI users. VRS was also correlated with the language composite score in the CI sample but not in the NH controls. Unlike VRS, however, perceptual encoding speed was unrelated to speech perception composite scores in the CI sample; it was also unrelated to the language composite scores in both groups.

Correlations of Verbal Rehearsal Speed and Perceptual Encoding Speed With Executive Function Measures for CI and NH Samples

Table 3 also displays a summary of the correlations obtained between the VRS and perceptual encoding speed measures with composite scores for the three EF domains (verbal working memory, fluency-speed, inhibition-concentration) for the CI and NH samples. Different patterns of correlations were observed for VRS and perceptual encoding speed with the three EF domains.

VRS and EF domains. After adjusting for multiple correlations, the relations between VRS and the three EF composite scores failed to reach significance in the CI group. However, VRS was significantly correlated with both the verbal working memory composite and the fluency-speed composite scores in the NH controls.

Perceptual encoding speed and EF domains. In contrast to VRS speed, which was related to EF only for the NH sample, the perceptual encoding speed composite was strongly and significantly correlated with all three EF domains for both the CI and NH samples; faster naming speeds were related to better verbal working memory, fluency-speed, and inhibition-concentration composite scores.

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Table 4. Correlations (and *p* values)[a] of VRS and perceptual encoding speed with participant demographic and hearing characteristics.

	VRS				Perceptual encoding speed			
	McGarr utterance duration				Composite			
	CI		NH		CI		NH	
Variable	Correlation	p	Correlation	p	Correlation	p	Correlation	p
Age (years)	−.04	.80	−.25 (.15)	.15	.51	<.001	.63	<.001
Income	−.29	.12	−.04 (.80)	.80	.07	.75	.05	.80
Wechsler Abbreviated Scale of Intelligence Matrix Reasoning T-score	.11	.67	.10 (.72)	.72	−.12	.63	−.13	.60
Age at implant (months)	.04	.80			.47	<.001		
Years of implant use	−.07	.75			.45	.003		
Onset of deafness (months)	−.001	.99			.31	.06		
Best pre-implant pure-tone average	.15	.49			−.09	.73		
CMRS	−.22	.23			.04	.80		

[a]Benjamini-Hochberg adjusted *p* values.

Recently Kronenberger et al. (2013) reported that conventional demographic and hearing loss factors were not significant predictors of the EF measures. However, as a precaution, we report the partial correlations of VRS and perceptual encoding speed with the composite scores for speech, language, and the three EF domains while controlling for chronological age (online supplemental Table 11). For perceptual encoding speed, all correlations with the three EF domains remained strong and significant after controlling for age (absolute value of all *r*s > .53 and all *p*s < .01 for CI users; absolute value of all *r*s > .44 and all *p*s < .01 for NH sample). In the NH group, the correlations of VRS with verbal working memory ($r = -.25$, $n = 55$, $p = .07$) and fluency-speed ($r = -.23$, $n = 55$, $p = .10$) were no longer significantly correlated after controlling for age. However, this is to be expected as the increase in speed and efficiency of verbal rehearsal through typical development has been well documented in the cognitive and developmental literature (Hulme et al., 1984; Hulme & Tordoff, 1989; Jarrold & Hall, 2013; Jarrold & Tam, 2011).

Discussion

As expected, CI users displayed slower VRS and perceptual encoding speed than NH controls (Predictions 1 and 4). However, CI users also displayed a fundamentally different profile of correlations among VRS and speech, language, and EF skills compared to the NH control group. The observed patterns suggest that NH listeners, whose VRS measurements were correlated with both verbal working memory and fluency-speed domains, routinely engaged covert speech strategies to regulate and control their behavior and that the speed of covert speech processes affects their EF performance (Prediction 2). In the CI group, VRS was correlated with both the speech and language composites but with none of the EF domains (Prediction 3). Conversely, perceptual encoding speed was strongly related to all three EF domains in both groups (Prediction 5). This pattern was expected because perceptual encoding is a mandatory elementary process in all tasks, whereas verbal rehearsal and other forms of covert speech are considered to be optional and not necessary for carrying out all information processing tasks (Barkley, 2012; Morey et al., 2013; Turley-Ames & Whitfield, 2001).

The statistically significant relations observed between VRS, perceptual encoding speed, speech-language, and EF composite scores found in this study displayed effect sizes in the medium range or higher (Cohen, 1992), showing at least 11% (e.g., verbal working memory composite and VRS for NH sample) and as much as 37%–69% (correlations between perceptual encoding speed and EF composites) of shared variance between measures for statistically significant results. Whereas statistical significance provides an estimate of likelihood that results are due to chance, the size of correlations (e.g., effect size) provides information about the magnitude of those effects (e.g., amount of shared variance). In the present study, the sizes of statistically significant correlations were in the medium range and were consistent with a magnitude of effect size used to justify evidence-based interventions (Meyer et al., 2001). In the sections below, we discuss each of our primary findings, focusing on the results that highlight differences between the two samples.

Patterns of Verbal Rehearsal Speed With EF Tasks

As we have previously reported, long-term CI users displayed slower overt articulation rates than the NH controls as measured by duration of seven-syllable McGarr Sentence utterances, demonstrating that despite having more than 7 years of experience with their CIs, when these CI users engage self-directed covert speech—including covert verbal rehearsal—they likely do so more slowly and less efficiently than their NH peers. To better understand the role of speed/efficiency of covert speech in carrying out executive function tasks, we correlated VRS with composite scores representing three EF domains known to be at risk in the CI population: (a) verbal working memory, (b) fluency

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speed, and (c) inhibition-concentration (Kronenberger et al., 2013).

Verbal rehearsal speed, as a proxy for self-directed covert speech, was found to be significantly correlated with two of the three EF domains in the NH controls. Although not significant, the moderate effect size between VRS and the inhibition-concentration composite score observed in the present study is within the ranges previously reported for articulation rate and working memory span correlated at the participant level. For example, Cowan et al. (1998) reported significant Pearson *r* values from .28 to .49 for correlations between rapid articulation of two-, three-, or four-word lists and two different administrations of digit span. This suggests that the present study may not have been powerful enough to detect a significant relation in the inhibition-concentration domain. The present findings are consistent with Barkley's (2012) proposal that self-directed covert speech can be used to control and guide behavior during EF tasks, and that within a group of NH typically developing individuals, the speed/efficiency of using covert speech mechanisms contributes to individual differences in EF.

The precise relations between VRS and the execution of EF tasks by the CI users is less clear. It would be, perhaps, too strong a claim to suggest that CI users never employ self-directed covert speech as a mediation strategy during EF tasks. The use of self-directed covert speech may vary over individuals as well as over situations. However, our findings suggest that this strategy is not a robust predictor of individual differences in long-term CI users in the three EF domains found by Kronenberger et al. (2013) to be at risk in this population.

Although the stimuli (e.g., digits, letters, pictures of concrete nouns) of many of the EF tasks used by Kronenberger et al. (2013) could be optionally verbalized, the authors purposefully chose executive function tasks that minimized auditory input and spoken responses. It is possible that requiring overt speech perception or spoken responses may encourage more CI users to engage a verbal mediation strategy. This suggestion is consistent with the earlier proposal of Gillam, Cowan, and Marler (1998) that some children with specific language impairment failed to utilize verbal recoding and verbal rehearsal strategies in simple memory span tasks that did not explicitly require auditory-verbal demands in perception or production. However, these children with specific language impairment did actively use verbal strategies when they received auditory input or were explicitly required to verbally report their response.

Patterns of Perceptual Encoding Speed With EF Tasks

Because rapid naming tasks require efficient retrieval of verbal codes and inhibition of previous competing responses from long-term memory, it is also not surprising that the perceptual encoding speed composite was found to be strongly related to all three EF domains for both groups of participants, providing additional converging support for our hypothesis that elementary foundational neurocognitive mechanisms are inseparable components of information processing systems and contribute to the observed individual differences in end point speech and language product measures. Studying these foundational underlying processes provides new insights into the enormous variability and individual differences in the speech perception and language outcomes universally reported in all CI centers. Moreover, the finding that long-term CI users do not utilize covert verbal rehearsal processes in the same manner or to the same extent as their NH peers provides additional knowledge about the basis of atypical development of speech perception, language, and executive function skills in deaf children following long-term CI use.

One consideration in proposing that articulation rate and speeded naming reflect internal timing constraints that limit information processing in other tasks is that measures of McGarr utterance duration and rapid naming both impose speech-motor control requirements that may impose a differential cognitive load on the CI users compared to NH listeners. Individual differences in cognitive load, rather than individual differences in speed and efficiency of covert speech, may underlie the relations between VRS, perceptual encoding speed, and the EF domains used here. An alternative account of the relation between articulation rate and verbal working memory presented earlier suggests that this relation could emerge not from development of VRS, but rather from the development of more robust and efficient speech-motor output processes during verbal recall of working memory tasks (Jarrold & Hall, 2013). However, Jarrold and Hall (2013) also suggested that if verbal rehearsal does develop during childhood, it may be constrained by the capacity of working memory and the quality (i.e., perceptual robustness and specificity) of the phonological representations maintained in active working memory. Their interpretation is consistent with our proposal that the atypical auditory development experienced by long-term CI users results in underspecified phonological representations of words in verbal working memory, which reduces optimal and efficient use of covert verbal rehearsal strategies and other forms of self-directed covert speech.

Taken together, the findings obtained in the present investigation suggest that the traditional end point product measures of speech and language outcomes used to assess the benefits of CIs in deaf children should be substantially broadened to include other information processing domains that rely heavily on executive functioning and cognitive control processes such as working memory dynamics, fluency-speed, and inhibition-concentration. Measures of these foundational skills and the core elementary information processing operations that underlie them may provide further insights about the underlying sources of individual differences and variability in the conventional speech and language outcome measures typically used to assess the benefits of CIs in deaf children and adults.

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