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Verbal learning and memory in prelingually deaf children with cochlear implants

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Abstract

Objective: Deaf children with cochlear implants (CIs) show poorer verbal working memory compared to normal-hearing (NH) peers, but little is known about their verbal learning and memory (VLM) processes involving multi-trial free recall.

Design: Children with CIs were compared to NH peers using the California Verbal Learning Test for Children (CVLT-C).

Study sample: Participants were 21 deaf (before age 6 months) children (6–16 years old) implanted prior to age 3 years, and 21 age-IQ matched NH peers.

Results: Results revealed no differences between groups in number of words recalled. However, CI users showed a pattern of increasing use of serial clustering strategies across learning trials, whereas NH peers decreased their use of serial clustering strategies. In the CI sample (but not in the NH sample), verbal working memory test scores were related to resistance to the build-up of proactive interference, and sentence recognition was associated with performance on the first exposure to the word list and to the use of recency recall strategies.

Conclusions: Children with CIs showed robust evidence of VLM comparable to NH peers. However, their VLM processing (especially recency and proactive interference) was related to speech perception outcomes and verbal WM in different ways from NH peers.

Keywords

Deafness; learning; memory; working memory; speech perception; cochlear implant

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Cochlear implants (CIs) are the most effective sensory prosthetic devices, allowing the restoration of components of hearing to individuals with severe to profound deafness (Kral et al. 2016). For prelingually deaf children and adolescents, the introduction of hearing experience supports the development of speech perception and spoken language skills and also presents the developing brain with auditory experience that would otherwise be minimal or absent during early stages of development (Kral et al. 2016). Prelingually deaf children who receive CIs represent a unique population because they do not have the benefit of hearing or exposure to language during early neurological/psychological development and develop spoken language only after cochlear implantation. Thus, spoken language development, as well as the influence of spoken language development on other neurocognitive abilities, is dependent on input and experience provided by the CI.

Speech perception and spoken language development occur rapidly following cochlear implantation in young children (Geers and Sedey 2011), although there is enormous variability in outcomes (Niparko et al. 2010). Explaining this variability in speech perception and language outcomes, with the goal of developing targeted interventions, is one of the most important research and clinical goals in the field of paediatric cochlear implantation (Pisoni et al. 2008, 2016). Factors such as earlier age at implantation, shorter duration of deafness before implantation, better residual hearing prior to implantation, quality of speech-language rehabilitation and use of auditory-oral language modalities predict positive speech and language outcomes following implantation (Geers and Sedey 2011; Pisoni et al. 2008), but a significant amount of variance in speech-language outcomes remains to be explained.

In addition to developmental effects on speech perception and spoken language skills, cochlear implantation also produces changes to other brain functions and abilities, broadly referred to as “neurocognitive abilities.” No part of the brain develops or acts entirely in isolation, and changes in early experience and functioning in one part of the brain impact the development of other neurocognitive abilities and brain functions (Kral et al. 2016). Exposure to auditory signals affects multiple domains of neurocognitive development, including sequential processing, auditory attention and spoken language processing (Conway et al. 2009; Kral et al., 2016). Moreover, language is critical for the development of neurocognitive functions such as short-term memory, reasoning and executive functioning (Gathercole and Baddeley, 1993; Petersen et al. 2013).

One well-studied subdomain of neurocognitive functioning in prelingually deaf children following cochlear implantation is verbal short-term/working memory (Nittrouer et al. 2013; Pisoni et al. 2011). Verbal short-term memory is a broad term for language-based immediate memory held in the phonological loop (Baddeley 2012), whereas verbal working memory (verbal WM) is a subcomponent of verbal short-term memory that reflects memory operations concurrent with additional cognitive processing load (Engle et al. 1999). The presence of concurrent load requires the active management of cognitive resources, reflecting the activity of the central executive (Baddeley 2012) and use of executive functioning (EF) (Diamond 2013). Given the degraded, underspecified input of speech signals provided by a CI, any verbal memory task likely requires an additional processing load greater than would be the case for a normal-hearing (NH) peer. Thus, while the

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neurocognitive processes of verbal "short-term" and verbal "working" memory may be represented on a continuum of concurrent cognitive load, for CI users, almost all verbal short-term memory tasks include a significant verbal WM component, and verbal WM is therefore used in this manuscript to refer to verbal short-term/working memory tasks.

Studies of verbal WM in samples of prelingually deaf, early implanted children with CIs, such as forward and backward word or digit span tasks, have found deficits relative to NH peers (Kronenberger et al. 2014; Nittrouer et al. 2013; Pisoni et al. 2011). Although most of the current research on verbal memory in children with CIs has used a verbal WM paradigm, there are other important domains, components, and functions of verbal memory. One informative paradigm for investigating verbal memory and learning processes is the multi-trial free recall paradigm (Delis et al. 1994, 2000). In this procedure, the subject is presented with multiple trials using the same list of words, so that verbal memory and learning following repetition can be investigated. The list is supraspan (e.g. exceeds the typical immediate memory span for the subject for one exposure), so that incremental learning and changes in self-generated organisational learning strategies can be observed across trials, and any order of item recall is accepted as accurate, allowing for subjects to use their own strategies in storage and retrieval. Verbal learning and memory (VLM) tests assess components related to verbal memory that are not assessed by typical span-based verbal WM tests, such as memory for words independent of recall order requirements, memory for supraspan word lists, learning curve across multiple trials, interference effects, decay, primacy, recency, serial and semantic recall organisation strategies (Delis et al. 1988).

VLM tests are considered to be ecologically valid because they measure memory and learning components that are routinely used in everyday language processing tasks (Pisoni et al. 2016). For example, in everyday interactions and learning, information is often repeated, based on the assumption that the individual will retain more in memory following each repetition. Interference is frequently encountered in memory, as people are required to remember one set of information immediately after a previous task (proactive interference) and immediately prior to the next task (which may involve a new, competing set of information to be remembered; retroactive interference). Additionally, better memory for items presented at the beginning (primacy) or at the end (recency) of a sequence is a well-established principle in studies of NH individuals (Delis et al. 1988). Importantly, none of these principles of learning and memory can be evaluated in traditional single-exposure span-based immediate memory tasks. As a result, very little is currently known about VLM in prelingually deaf, early implanted children with CIs.

Three studies have investigated VLM in adult CI users, two of which used samples of adults who received CIs after many years of experience with spoken language (postlingually deaf adults) (Heydebrand et al. 2007; Holden et al. 2013), and one of which used a sample of young adult CI users (17–29 years of age) who were deaf prior to age 3 years (Pisoni et al. 2016). Studies with postlingually deaf adults demonstrated positive correlations between measures of verbal WM and number of words recalled across multiple learning trials of a VLM test (the California Verbal Learning Test, Second Edition, Adult Version; CVLT-II) (Delis et al. 2000). Furthermore, total number of words recalled across trials accounted for a large amount of the variance in speech recognition scores after implantation (Heydebrand et

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al. 2007). A study of prelingually deaf (prior to age 3 years), young adult long-term CI users found that NH control subjects recalled more words on the CVLT-II than CI users, and the score for total words recalled correlated significantly with EF measures of controlled fluency-speed (controlled attention to complete concentration-intensive, goal-related tasks under time pressure) (Pisoni et al. 2016). Moreover, the NH sample showed a pattern of increasing use of self-generated semantic clustering strategies to support recall (i.e. grouping words based on semantic categories during recall) across trials (the first word list), while the CI sample showed no evidence of semantic clustering (Pisoni et al. 2016).

The current study is the first systematic investigation of VLM in prelingually deaf, early implanted children with CIs using a well-known, standardised measure of VLM, the California Verbal Learning Test for Children (CVLT-C) (Delis et al. 1994). We sought to investigate several questions about VLM in children with CIs:

1. How do the number of words recalled and processing components of VLM compare in children with CIs and matched, NH peers? Based on prior research with verbal WM measures and with adult VLM measures, we expected that children with CIs would recall fewer words and show a slower rate of learning new words following repetition.
2. How does VLM relate to verbal WM in children with CIs, compared to matched, NH peers? Verbal WM is a domain of memory that has been more extensively studied in CI users than VLM. Furthermore, verbal WM delays have been consistently found in samples of children with CIs (Pisoni et al. 2011). We expected to find modest-to-strong correlations between VLM and verbal WM in CI users since both processes require storage and retrieval of verbal information from memory and because cognitive control processes support both VLM and verbal WM.
3. How does VLM relate to speech perception in children with CIs, compared to matched NH peers? Understanding variability in speech perception outcomes is one of the most important research goals in the field of cochlear implantation. Better speech perception was expected to relate more strongly to better VLM performance in CI users than NH peers because stronger VLM performance likely reflects stronger spoken language fluency and more robust internal phonological-lexical representations of language in CI users.

Method

Participants

The sample consisted of 21 children and adolescents with cochlear implants (CI sample) and 21 age-nonverbal IQ matched normal-hearing peers (NH sample). Participants were recruited from a larger study of long-term CI users and NH peers that has been described previously (Kronenberger et al. 2013).

Inclusion criteria for the CI sample were as follows:

1. Severe to profound hearing loss (>70 dB HL) prior to age 1 year.

2. Cochlear implantation prior to age 3 years.
3. Use of CI for 7 years or more.
4. Use of a modern, multichannel CI system.
5. Enrolled in a rehabilitative programme that encourages the development of spoken language skills.

Inclusion criteria for both the CI and NH samples were as follows:

1. Aged 7–16 years.
2. English-speaking household.
3. No other neurological or neurodevelopmental disorders or delays documented in chart or reported by parents.
4. Nonverbal IQ > 70 as measured by the Comprehensive Test of Nonverbal Intelligence, Second Edition (CTONI2) (Hammill et al. 2009) Geometric Scale (nonverbal IQ composite).

NH sample participants were matched 1:1 individually with participants in the CI sample such that each matched pair were within 2 years of age and had nonverbal IQ within 1 SD (17/21 matches were within 1 year in age and 0.5 SD on IQ).

Sample characteristics are summarised in Table 1. Selfidentified race of participants in the CI and NH samples were White ($N = 19$ and 14, respectively), Asian ($N = 1$ and 2, respectively), Black (0 and 1) and more than 1 race (1 and 4). Samples did not differ in gender ($X^2(1) = 0.38$, $p = 0.53$), age or income (Table 1).

Because 19/21 participants in the CI sample were deaf at birth (the other two participants were identified as deaf at ages 2 and 6 months), duration of deafness and age at cochlear implantation were almost identical ($r = 0.98$). Etiology of deafness was unknown for 10 participants, familial of unknown aetiology ($N = 6$), Mondini malformation ($N = 2$), auditory neuropathy ($N = 1$), ototoxity ($N = 1$) and meningitis ($N = 1$). All subjects communicated using an Auditory-Oral communication mode (no sign).

Procedure

Study procedures were approved by the local institutional review board, and written consent and assent were obtained prior to initiation of study procedures. Participants were tested in a single evaluation session during which they were administered tests of speech perception, memory, learning and intellectual ability. Speech perception tests were presented to subjects in the quiet at 65 dB using a high-quality loudspeaker located approximately 3 feet from the subject. All other tests were administered using standardised directions that were identical for the CI users and NH peers.

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Measures

Nonverbal intelligence

Comprehensive Test of Nonverbal Intelligence, Second Edition (CTONI-2).— The CTONI-2 (Hammill et al. 2009) is a measure of nonverbal reasoning and concept formation. For this study, participants completed only subtests using abstract visual design stimuli, yielding a norm-based standard score reflective of nonverbal (fluid) IQ: the Geometric Scale. The CTONI-2 provides an estimate of nonverbal intelligence with reduced language input; it has excellent reliability and validity and has been used with populations with hearing loss and/or language delays (Hammill et al. 2009).

Verbal learning and memory

California Verbal Learning Test for Children (CVLT-C).—The CVLT-C is a multi-trial free recall verbal learning and memory test for children aged 5–16 years. Participants are read a list of 15 words (presented as a “Monday shopping list,” List A) five times using live voice presentation and are asked to recall as many words as possible in any order after each of the 5 trials. List A words are read in the same order for every trial and are from three semantic categories (clothing, toys and fruits), which are distributed throughout the list. Subjects are not informed of the semantic categories during the five List A repetition trials. Immediately after List A Trial 5, participants are read a new 15word shopping list (the “Tuesday shopping list,” List B) and recall words from that list in any order. List B words also fall into 3 semantic categories, one of which overlaps with a List A category and two of which do not. Following List B, participants are asked to recall as many words as they can from List A, without having List A presented again (Short Delay Free Recall). Participants are then asked to recall words from List A within each of the three categories, with the examiner providing each semantic category explicitly (Short Delay Cued Recall). After the Short Delay Cued Recall Trial, there is a 20-min delay period. After the delay period, participants are again asked to recall words from List A in a free recall format (Long Delay Free Recall) followed by a cued recall format (Long Delay Cued Recall). Finally, the examiner reads a list of 45 words, with the 15 List A words embedded along with 30 distractor words, and participants are asked to identify whether each word was on List A or not (List A Recognition). For the present study, only measures based on free recall trials were investigated because our focus was on free recall VLM.

The CVLT-C provides scores reflecting several foundational domains of VLM: Free recall scores provide measures of the number of words correctly recalled for each trial or summed across all five repetition learning trials. List A Trial 1 and List B scores (free recall scores) reflect list-based immediate verbal memory following a single exposure to material (the word list). However, List B recall reflects the effects of proactive interference (as a result of earlier-learned items [List A Trials 1–5] interfering with memory for List B items). List A Trial 5 is a measure of verbal learning and memory following multiple (five) exposures to a word list. The Short Delay Free Recall trial measures retroactive interference (as a result of later-learned verbal items and processing [List B] interfering with earlier-learned items [List A]). The Long Delay Free Recall trial measures decay of memory over a 20-min delay period.

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The CVLT-C also provides several measures that assess processing operations used during memory, learning and recall of the word list (“process measures”). Primacy Recall for the current study was defined as the percentage of the first four words on the list (either List A or List B) that were recalled after each trial or set of trials; for example, if two words from the first four words of List A were recalled for a Trial, the List A Primacy Recall score would be 2/4 = 50%. Conversely, Recency Recall was defined as the percentage of the final four words on the list that were recalled for each trial or set of trials; Prerecency Recall was defined as the percentage of the middle 7 words on the list that were recalled for each trial or set of trials. Hence, Primacy Recall scores reflect rehearsal of early items on the list, secondary memory (durable, cue-dependent search component of working memory that is not actively rehearsed/maintained (Unsworth and Engle 2007)), or a primacy effect (tendency to remember information presented first) in verbal learning and memory. In contrast, Recency Recall scores reflect retrieval of items from auditory sensory memory, primary memory (maintenance of specific memory representations using active, controlled attention) or a recency effect (tendency to remember the most recent information presented).

Another set of CVLT-C process measures assess how material is organised, stored and/or self-cued for free recall. The Semantic Cluster Ratio is an index of the extent to which words recalled by the participant are grouped sequentially based on category membership (e.g. for List A, clothing, toys or fruits), such that items from the same semantic category follow each other in order in the participant’s recall. The Semantic Cluster Ratio is corrected based on the extent to which serial grouping by category would occur by chance, such that a ratio of observed (actual recall by participant) semantic occurrences divided by expected (by chance) semantic occurrences is obtained. The Serial Cluster Ratio is an index of the extent to which words that are adjacent on the word list are recalled by the participant in the same order as read by the examiner. Serial clustering indicates rote recall (recall based on a direct internal representation of the examiner’s presentation of the words) or rehearsal.

In this study, we examined free recall and process measures of verbal learning and memory using five free recall scores from the CVLT-C (number of words recalled from List A Trial 1, List A Trial 5, List B, Short Delay Free Recall and Long Delay Free Recall) and eight process scores from the CVLT-C (Primacy, Recency, Semantic Cluster Ratio and Serial Cluster Ratio scores obtained for List A Trials 1 to 5 Total [e.g. averaged across all 5 immediate free recall trials of List A] and List B). Raw scores were used for all measures.

Sentence recognition

Four sentence recognition tests were used to obtain a broad assessment of speech understanding. The sentence recognition tests included a basic single-talker-in-the-quiet sentence recognition test, two tests using multiple talkers with different dialects, and a test that provided no contextual cues. By using a set of measures that varied based on number of talkers, dialect/accent and availability of contextual cues, we sought to obtain a broad assessment of sentence recognition skills that was more ecologically valid and linguistically diverse than one test using a single-talker in the quiet. Use of four different types of sentence recognition tests also provided a more stable assessment of speech perception than a single measure that could be influenced by test-specific properties. The three sentence recognition

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tests that vary talker, accent/dialect and context are more challenging than conventional clinical sentence recognition measures such as the Hearing in Noise Test (HINT) (Nilsson et al., 1996), because they make greater processing demands on memory, attention, inhibition, and encoding indexical attributes of speech signals such as talker and regional dialect. These types of demands are routinely encountered in real-world speech perception. In addition to greater ecological validity, most of these measures do not have the disadvantage of ceiling effects in NH samples because of their more complex and challenging features.

Harvard Standard Sentences (Harvard-S).—Participants repeated 28 semantically complex, meaningful sentences taken from the IEEE corpus (IEEE) (Egan 1948, IEEE 1969). Sentences were produced in the quiet by one male talker and consisted of 6–10 total words (mean =8.0 words), with five words per sentence identified as keywords (e.g. “The <u>boy</u> was <u>there when</u> the <u>sun rose</u>”). Raw scores were the percentage of keywords correctly repeated.

Harvard Anomalous Sentences (Harvard-A).—The Harvard-A sentence test is similar to the Harvard-S, except that the sentences are not semantically meaningful. Participants repeated 28 grammatically correct, semantically meaningless sentences modified from the IEEE corpus (Loebach and Pisoni 2008). Sentences were produced in the quiet by one male talker and consisted of 5–10 total words (mean = 7.7 words), with five words in each sentence identified as keywords (e.g. “<u>These dice bend</u> in a <u>hot desk</u>”). Raw scores were the percentage of keywords correctly repeated.

Perceptually Robust English Sentence Test Open-Set (PRESTO).—The PRESTO is a sentence recognition test consisting of 30 sentences drawn from the TIMIT database (Garafolo et al. 1993). Each sentence is spoken by a different male or female talker selected from one of six regional United States dialects, requiring the listener to rapidly adapt to changes in the vocal sound source (Gilbert et al. 2013; Tamati et al. 2013). PRESTO scores reliably detect subtle differences in speech recognition performance (Tamati et al. 2013) and have good psychometric properties (Gilbert et al. 2013).

PRESTO-Foreign Accented English (PRESTO-FAE).—The PRESTO-FAE is a new version of PRESTO in which sentences are spoken by non-native English speakers who differ in degree of foreign accent (Tamati and Pisoni 2015). The 26 sentences in PRESTO-FAE are drawn from the SPIN sentences list (Kalikow et al. 1977). Because perception of sentences spoken by individuals with unfamiliar non-native accents can be very challenging, it was anticipated that this test would not show ceiling effects in the NH group, allowing for variability in sentence recognition scores in that group without having to degrade the test signals (Tamati and Pisoni 2015).

Verbal working memory

Computerized Visual Digit Span Test (CDS).—The CDS is a computer-administered measure of verbal WM using visual presentation of digits and touchscreen responses on a computer touchpad (AuBuchon et al. 2015). Subjects are presented with a random sequence of digits (1–9) that they must reproduce in either forward (Digit Span Forward) or reverse

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(Digit Span Backward) order on a 3 × 3 response grid using a manual touchscreen (12.1 inch, 800 × 600 pixel, Model Keytec L1201S). The number of digits in the sequences begins with 2 digits (presented sequentially at 1 second intervals) and then increases by 1 digit after every 2 trials until 2 trials are failed at the same sequence length (ceiling level). Raw scores are the number of digit sequences reproduced correctly forward or backward. The CDS has been validated in samples of CI users (AuBuchon et al. 2015).

Computerized Visual Object Span Test (COS).—The COS was developed as an additional measure of verbal WM for the present study, based on the CDS, using visual images of 9 common objects instead of digits. Subjects reproduce the series of objects in either forward or backward order using a touchscreen. The presentation format and scoring procedures for the COS are identical to those for the CDS.

Statistical analysis

Initial statistical analyses consisted of descriptive statistics and group comparisons using *t*-tests for continuous variables and chi-square tests for categorical variables. Next, in order to reduce the number of variables measuring sentence recognition and verbal WM, principal components analysis and inspection of correlation matrices were used to create single composite scores representing those constructs. Finally, correlations were used to evaluate associations between VLM and demographics/hearing history, nonverbal IQ, sentence recognition, and verbal WM.

Results

Sample descriptions and comparisons

Demographics, Hearing History, and Nonverbal IQ.—Sample descriptions for demographics, hearing history and nonverbal IQ scores are reported in Table 1. No significant differences were found in any of these measures. Both samples had nonverbal intelligence scores well above the norm mean of 100 (for CI, $t(20) = 4.00$, $p < 0.001$; for NH, $t(20) = 3.09$, $p < 0.006$).

Sentence Recognition and Working Memory.—As expected, the NH sample scored higher on measures of sentence recognition than the CI sample ($p < 0.001$; see Table 1). No subject from either sample reached a ceiling (e.g. 100% of keywords recalled correctly) on the PRESTO-FAE or Harvard-A sentence recognition tests. On measures of verbal WM, the CI sample scored significantly lower than the NH sample on the Digit Span Backward ($p < 0.05$) and Object Span Forward ($p < 0.01$) tests. Group differences for Digit Span Forward ($p = 0.12$) and Object Span Backward ($p = 0.11$) tests were in the expected direction but nonsignificant.

Results of principal components analyses (PCA) of the four sentence recognition scores (Harvard-S, Harvard-A, PRESTO and PRESTO-FAE) strongly supported a single component with eigenvalue of 3.815 accounting for 95.4% of variance (the next largest eigenvalue was 0.246). Intercorrelations between the four sentence recognition scores ranged from 0.87 to 0.98 (all $p < 0.001$). Results of the PCA of the four verbal WM tests (Digit

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Span Forward and Backward; Object Span Forward and Backward) also supported a single component with eigenvalue of 2.708 accounting for 68.0% of variance (the next largest eigenvalue was 0.587). Intercorrelations between the four verbal WM scores ranged from 0.46 to 0.65 (all $p < 0.003$). Based on these PCA results, z-scores (using the mean and standard deviation in the combined CI and NH sample) for the four sentence recognition tests were averaged to obtain a single aggregate global sentence recognition score, and *z*-scores for the four verbal WM tests were averaged to obtain a single aggregate global verbal WM score (Kronenberger et al. 2014). The CI sample scored lower than the NH sample on global sentence recognition and global verbal WM (Table 1).

Verbal Learning and Memory.—Both the CI and NH samples showed the expected pattern of increases in words recalled with repeated exposure to List A (Figure 1). No differences were found between the CI and NH samples on any of the List A or List B number of words recalled, primacy, recency or semantic clustering scores (Table 2). On the other hand, the NH sample showed significantly more serial clustering during the List A trials, whereas the CI sample showed significantly more serial clustering during the List B trial (Table 2). Furthermore, the pattern of serial clustering across trials differed substantially between groups: The NH group showed a pattern of declining serial clustering during repetition exposure to the list learning task, whereas the CI sample showed the opposite pattern, with increasing use of serial clustering during repetition exposure to the list learning task (Figure 2).

As a validity check to assess the audibility of the CVLT-C test words, subjects were read the word lists after completion of the CVLT-C and were asked to repeat each word aloud to the examiner. For List A, all subjects in both groups repeated all test words accurately. For List B, only 1 word was repeated incorrectly by 1 subject in the CI group, resulting in no significant difference between the groups ($p = 0.32$; Table 2).

Correlations of verbal learning and memory scores with demographics, hearing history, verbal working memory and sentence recognition

Demographics and Hearing History.—Few significant associations were found between demographics and hearing history variables and the CVLT-C scores. The only consistent relationships were for older age and years of CI use to be correlated ($p < 0.05$) with List A Trial 5 ($r = 0.45$ and 0.49, respectively) and Short Delay Free Recall ($r = 0.53$ and 0.57). Otherwise, no demographics or hearing history variable was associated with more than one free recall score or with one process score (a table of all correlations is available from the authors).

Sentence Recognition and Verbal WM.—In the CI sample, better sentence recognition scores were related to higher List A Trial 1 free recall and recency recall scores (Table 3). In the NH sample, sentence recognition scores were positively related to number of words recalled for every List A Trial. Although both verbal WM and List A Trial 1 assess immediate memory, they were uncorrelated in the CI and NH samples. For CI users, verbal WM correlated significantly with List A Trial 5 and List B, whereas for NH participants, verbal WM was significantly associated only with the List A scores after repetition exposure

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(Trial 5, Short- and Long-Delay Free recall). Verbal WM was not significantly related to CVLT-C process measures in either sample.

Discussion

This study is the first systematic investigation of multi-trial free recall verbal list learning and memory (VLM) in prelingually deaf, early implanted children and adolescents with CIs. Three primary research questions about VLM were addressed: (1) how do children with CIs compare to closely-matched NH peers in VLM number of words recalled and process measures; (2) how does VLM relate to verbal WM in children with CIs compared to NH peers; and (3) how does VLM relate to sentence recognition in children with CIs?

Contrary to our initial hypotheses, children with CIs and NH peers showed no differences on measures of VLM number of words recalled during any free recall trial. This finding contrasts markedly with the frequent finding of significant delays in CI samples in verbal WM on single-exposure, sequential, rote memory tasks such as digit span, word span, and object span tasks (AuBuchon et al. 2015; Nittrouer et al. 2013; Pisoni et al. 2011). The current sample also showed lower scores relative to NH peers on an aggregate measure of verbal WM based on those types of tasks, consistent with the body of prior research, which suggests that the findings of no differences in CVLT-C number of words recalled are not simply a result of having an unusual sample of children with CIs.

In contrast to consistent findings of lower verbal WM scores in CI compared to NH samples in this and prior studies, the finding of no differences between the CI and NH samples in words recalled on CVLT-C trials in the current study may reflect several possible factors. First, the free recall format of the CVLTC has no demands for encoding item-order information; words can be recalled in any order. It may be that the processing demands required for rote-sequential memory in traditional verbal WM measures exert an additional load that adversely affects CI users, who perform better under a free recall format that does not require simultaneous processing of both item and order information in sequencing and immediate memory. This account would be consistent with other research demonstrating selective weaknesses in sequential processing (Conway et al. 2009), less robust encoding of verbal material (and therefore more vulnerability to additional load) (Burkholder and Pisoni 2003; Pisoni et al. 2011, 2016), and/or executive functioning weaknesses (Kronenberger et al. 2013) in some deaf CI users. Additionally, the CVLT-C is a supraspan task, presenting the subject with more words than can be remembered following one exposure, whereas traditional verbal WM tests present sequences that are less than or equal to the child’s maximum immediate memory span. Therefore, for the CVLT-C, a significant component of the memory task is retrieval of as many items as possible from a large list (allowing for errors in sequencing or failure to recall some items), whereas verbal WM tasks call for complete reproduction of item and order information. The latter type of task presents greater processing load and less tolerance for error.

The lack of differences between CI and NH samples in CVLT-C number of words recalled belies some underlying differences in the process scores reflecting strategies and methods of verbal learning and memory. Serial clustering strategies used by the CI and NH samples

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differed markedly across List A and List B trials. The NH sample recalled words using the same serial order as presented by the examiner at a rate over 2.5 times chance for List A Trial 1, peaking at over 4 times chance for List A Trial 2 and dropping steadily thereafter to about 2–2.5 times chance by List A Trial 5 and only 1.5 times chance by List B. The CI sample, on the other hand, recalled words in serial order at only a chance level for List A Trial 1 but then steadily increased their use of serial clustering to 2 times chance by List A Trial 3, remaining at that level for the remainder of the List A immediate memory trials. For List B, the CI sample used serial strategies, on average, at a rate 3.5 times chance (Figure 2).

The marked differences observed in progression of use of serial recall strategies between the CI and NH groups may reflect the use of idiosyncratic, non-serial strategies for rehearsal and recall in the CI group for the early exposures to List A, perhaps as a result of lower spare information processing resources available for active memory strategies (Pisoni et al. 2016; Rönnberg et al. 2013) or sequential processing weaknesses (Conway et al. 2009). After several repetitions of List A, the CI sample relied more heavily on serial recall strategies, possibly reflecting greater spare processing capacity as familiarity with the task and test items improved.

Interestingly, correlations between sentence recognition and CVLT-C List A free recall scores were stronger and more robust in the NH sample than in the CI sample. For NH children, speech perception is more uniformly fast and automatic compared to children with CIs, as reflected in the higher mean and smaller SD in sentence recognition scores in the NH sample (Table 1). As a result, variability in sentence recognition test scores in the NH sample was likely driven primarily by individual differences in verbal short-term memory and less by speech perception differences. Strong associations between sentence recognition and List A free recall scores in the NH sample may therefore have occurred because they share a component of verbal short-term memory.

In contrast, children with CIs must process a degraded, underspecified signal concurrent with the memory demands of sentence recognition tests, resulting in greater influence of speech perception on sentence recognition scores compared to NH peers. In the CI sample, sentence recognition was strongly related only to the first trial of List A and to recency recall. List A Trial 1 is more dependent on robust speech perception skills because it is the first exposure to the word list (and therefore internal representations of the test stimuli are more fragile than for later List A trials). Recency recall is more dependent on robust speech perception skills because recency recall reflects auditory sensory memory that is affected by the quality of perceptual representations of auditory stimuli. As a result, in the CI sample, significant correlations between List A Trial 1, recency recall, and sentence perception may reflect primarily the shared components of speech perception and robust internal representation of language.

Verbal WM, on the other hand, was related to List A Trial 5 and List B in the CI sample. Free recall of List A Trial 5 items reflects repetition learning, while free recall of List B items reflects memory performance under adverse conditions of proactive interference. Both of these measures therefore require additional processing operations that reflect intentional recruitment and effortful deployment of resources to either benefit from repetition or to

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actively inhibit and resist the build-up of proactive interference. The relation of verbal WM with List A Trial 5 and List B in the CI group may therefore be a result of the ability to process verbal information under additional demands such as rote-sequential processing or concurrent cognitive load.

Several components of the methodology used in this study should be considered when interpreting results. First, both samples had mean nonverbal IQ scores over 100, and the CI sample consisted of very experienced users. Thus, it is possible that the present study results apply primarily to experienced, high-functioning samples of children with CIs. Second, the CI and NH samples were matched 1:1 on age and nonverbal IQ, removing possible confounds associated with sample age and nonverbal intelligence. Third, because the standard live-voice and spoken response format of the CVLT-C was used, it is possible that audibility and speech production demands could have influenced CVLT-C results, although results of the auditory accuracy trial showed no group differences (Table 2).

A fourth methodological consideration is the potential for ceiling effects on sentence recognition scores in the NH group, given that the sentence recognition tests were administered in the quiet. However, by using a set of challenging sentence recognition tests that varied in number of speakers, regional dialect, non-native accent, and contextual cues, we were able to obtain an adequate range of scores for sentence recognition in the quiet in both the CI and NH samples. However, we did not include a measure of sentence recognition in background noise, which would have provided additional breadth and challenge to our battery of sentence recognition tests; future research should include sentence recognition tests in noise. Finally, because results are based on samples of modest sizes, statistically significant results would be detected in the current analyses only for medium and larger effect sizes. We chose not to correct for multiple comparisons and correlations because of the exploratory nature of this first study of VLM in children and adolescents with CIs and because of the adverse effects that corrections would have on statistical power. We tried to minimise alpha error by using aggregate measures for verbal WM and sentence recognition and by emphasising patterns of results over isolated findings.

Conclusion

Results of this first study of VLM in prelingually deaf, early implanted children and adolescents with CIs provide evidence of similarities and differences compared to NH peers. CI and NH samples did not differ in VLM free recall as measured by the number of words recalled on each trial, demonstrating that young, early-implanted children with CIs can achieve levels of some components of VLM consistent with that of their NH peers. Furthermore, VLM was distinct from but related to verbal WM and speech perception in both samples, although relations between VLM, verbal WM and speech perception were different for CI and NH samples. Assessment of memory in children following cochlear implantation should include VLM assessment rather than assuming that single-exposure, rote memory measures such as digit span have captured the full-range of memory and learning processes.

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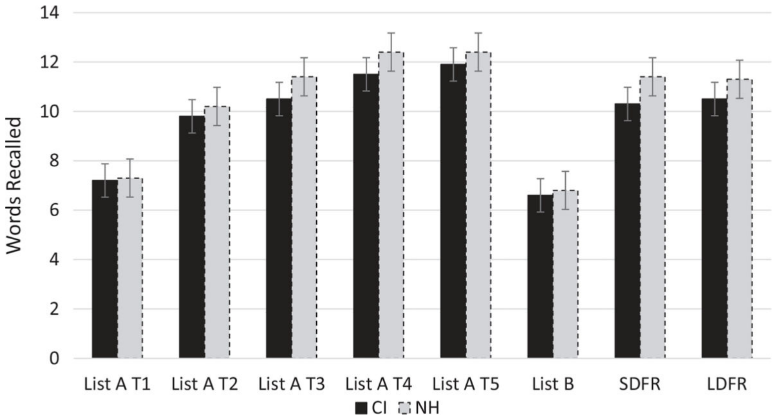

Figure 1.

California Verbal Learning Test for Children Free Recall Scores (Number of Words Recalled) by Trial for Cochlear Implant (CI) and Normal-Hearing (NH) Samples. Values are sample mean raw scores (number of words recalled) by trial; bars are standard error; T1: Trial 1; SDFR: List A Short-Delay Free Recall; LDFR: List A Long-Delay Free Recall.

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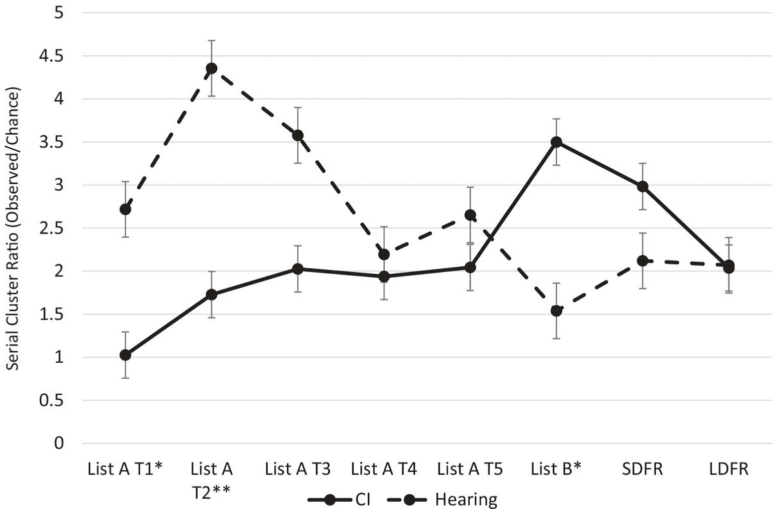

Figure 2.

California Verbal Learning Test for Children Serial Cluster Ratio by Trial for Cochlear Implant (CI) and Normal-Hearing (NH) Samples. Values are serial cluster ratio (observed serial clustering/chance serial clustering) sample mean scores; bars are standard error; T1: Trial 1; SDFR: List A Short-Delay Free Recall; LDFR: List A Long-Delay Free Recall. $*p<0.05$; $**p<0.01$.

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Table 1.

Sample characteristics

	CI sample		NH sample		
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	***t***
Demographics and Hearing History					
Chronological Age[a]	12.8 (2.5)	9.3–16.6	12.9 (2.1)	10.0–16.1	0.2
Age at Implantation[b]	22.8 (7.1)	8.2–35.8	NA	NA	
Duration of CI Use[a]	10.9 (2.5)	7.5–15.0	NA	NA	
Age of Onset of Deafness[b]	0.4 (1.4)	0–6	NA	NA	
Preimplant PTA[c]	105.8 (12.6)	85.0–118.4	NA	NA	
Communication Mode[d]	5.0 (0.0)	5–5	NA	NA	
Income Level[e]	8.4 (2.2)	3–10	7.4 (2.3)	1–10	1.5
Nonverbal Intelligence[f]	110.5 (12.1)	89–130	108.6 (12.7)	78–122	0.5
Sex (Female/Male)	10/11			12/9	
Sentence Recognition					
Harvard Standard	73.4 (18.7)	35–94	96.4 (3.7)	87–100	5.5***
Harvard Anomalous	52.5 (20.9)	16–89	88.8 (6.6)	72–97	7.6***
PRESTO	60.5 (21.2)	24–90	94.5 (6.0)	76–100	7.1***
PRESTO-FAE	42.8 (17.9)	0–75	78.9 (9.1)	56–88	8.2***
Sentence Recognition					
Composite[g]	–0.73 (0.87)	–2.25 to 0.42	0.73 (0.27)	0.01 −1.01	7.4***
Verbal Working Memory					
Digit Span Forward	7.7 (2.5)	5–14	8.8 (2.0)	6–13	1.6
Digit Span Backward	5.4 (2.1)	2–9	7.2 (3.3)	2–14	2.2*
Object Span Forward	5.3 (2.0)	0–9	6.9 (1.4)	3–9	3.1**
Object Span Backward	3.3 (2.2)	0–10	4.3 (1.7)	2–8	1.6
Verbal Working Memory					

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	CI sample		NH sample		
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	***t***
Composite[g]	–0.29 (0.82)	–1.69 to 1.41	0.31 (0.73)	–1.13 to 1.56	2.5 *

Note: CI: cochlear implant; NH: normal-hearing; df for *t*-tests = 40, with exception of Income (df = 36), Digit Span Backward (df=39), and Verbal Working Memory (df=39).

[a] in Years.

[b] in Months.

[c] PTA: preimplant unaided pure-tone average for frequencies 500, 1000, 2000 Hz in dB HL.

[d] Communication mode coded mostly sign (1) to auditory-verbal (6)(Geers and Brenner, 2003).

[e] On a 1 (under \$5,500) to 10 (\$95,000+) scale (Kronenberger et al. 2013).

[f] CTONI-2 Geometric Nonverbal IQ Composite Index (normed standard score).

[g] Domain scores are mean z-scores for constituent measures.

*** $p<0.001$

** $p<0.01$

* $p<0.05$.

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Table 2.

California Verbal Learning Test for Children (CVLT-C) Scores by Sample.

	CI sample Mean (SD)	NH sample Mean (SD)	*t*	*p*
Free Recall Scales (Number of Words Recalled)				
List A Trial 1[a]	7.2 (2.0)	7.3 (1.5)	0.17	0.86
List A Trial 2[a]	9.8 (2.6)	10.2 (1.4)	0.66	0.51
List A Trial 3[a]	10.5 (3.3)	11.4 (1.5)	1.14	0.26
List A Trial 4[a]	11.5 (2.3)	12.4 (1.7)	1.39	0.17
List A Trial 5[a]	11.9 (2.5)	12.4 (1.7)	0.85	0.40
List B Free Recall[a]	6.6 (2.1)	6.8 (1.4)	0.34	0.73
List A Short Delay Free Recall[a]	10.3 (3.5)	11.4 (2.2)	1.26	0.22
List A Long Delay Free Recall[a]	10.5 (2.9)	11.3 (2.1)	1.12	0.27
Process Scales				
Semantic Cluster Ratio[b]				
List A Trials 1–5	1.5 (0.4)	1.5 (0.4)	0.08	0.94
List B	1.3 (0.7)	1.4 (0.9)	0.34	0.74
Serial Cluster Ratio[b]				
List A Trials 1–5	1.9 (1.6)	3.1 (1.9)	2.19	0.03 *
List B	3.5 (3.8)	1.5 (2.3)	2.03	0.05 *
Primacy Recall[c]				
List A Trials 1–5	74.3 (17.3)	80.2 (10.9)	1.33	0.19
List B	56.0 (31.5)	61.9 (26.9)	0.66	0.52
Recency Recall[c]				
List A Trials 1–5	76.4 (14.9)	75.2 (12.6)	0.28	0.78
List B	61.9 (29.2)	58.3 (25.4)	0.42	0.68
Hearing Validity Scales				
List A Auditory Accuracy[d]	15.0 (0.0)	15.0 (0.0)	—	—

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	CI sample Mean (SD)	NH sample Mean (SD)	*t*	*p*
List B Auditory Accuracy[d]	15.0 (0.2)	15.0 (0.0)	1.00	0.32

Note: CI: cochlear implant; NH: normal-hearing. df for *t*-tests =40.

[a] Raw scores, based on number of items recalled.

[b] Ratio of observed:expected/chance contiguous recall clustering based on shared semantic category or serial position of word in the list.

[c] Values for primacy and recency recall are percentage of first four words on the 15-item word list or last four words on the 15-item word list (respectively) accurately recalled by subject.

[d] Number of words from the list accurately repeated immediately after spoken by examiner (max = 15).

[*] $p < 0.05$

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Table 3.

California Verbal Learning Test for Children (CVLT-C) Correlations with Sentence Recognition and Verbal Working Memory.

	Sentence Recognition		**Verbal Working Memory**	
	CI	**NH**	**CI**	**NH**
Free Recall Scales (Number of Words Recalled)				
List A Trial 1^{a}	0.44*	0.56**	0.11	0.06
List A Trial 5^{a}	0.23	0.61**	0.51*	0.48*
List B^{a}	0.36	0.19	0.49*	0.04
List A SDFR^{a}	0.10	0.78***	0.41a	0.57**
List A LDFR^{a}	0.12	0.64**	0.36	0.48*
Process Scales				
Semantic Cluster Ratio^{b}				
List A Trials 1–5	–0.20	–0.07	–0.25	–0.13
List B	–0.19	–0.08	–0.14	0.10
Serial Cluster Ratio^{b}				
List A Trials 1 –5	–0.12	0.09	0.11	0.40^{a}
List B	–0.16	0.02	–0.29	–0.05
Primacy Recall^{c}				
List A Trials 1 –5	–0.01	0.38a	0.19	0.15
List B	–0.21	0.02	0.07	0.03
Recency Recall^{c}				
List A Trials 1 –5	0.51*	0.31	0.13	0.09
List B	0 77***	0.17	0.40^{a}	–0.01

Note: Values are Pearson correlation coefficients; CI: Cochlear Implant sample; LDFR: Long Delay Free Recall; NH: Normal-Hearing sample; SDFR: Short-Delay Free Recall.

[a] Raw scores, based on number of items recalled.

[b] Ratio of observed:expected/chance contiguous recall clustering based on shared semantic category or serial position of word in the list.

[c] Values for primacy and recency recall are percentage of first four words on the 15-item word list or last four words on the 15-item word list (respectively) accurately recalled by subject.

[***] $p<0.001$

[**] $p<0.01$

[*] $p<0.05$

[a] $p<0.10$.

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