JSLHR

Research Article

Verbal Working Memory in Children With Cochlear Implants

Susan Nittrouer,[a] Amanda Caldwell-Tarr,[a] Keri E. Low,[a] and Joanna H. Lowenstein[a]

Purpose: Verbal working memory in children with cochlear implants and children with normal hearing was examined.
Participants: Ninety-three fourth graders (47 with normal hearing, 46 with cochlear implants) participated, all of whom were in a longitudinal study and had working memory assessed 2 years earlier.
Method: A dual-component model of working memory was adopted, and a serial recall task measured storage and processing. Potential predictor variables were phonological awareness, vocabulary knowledge, nonverbal IQ, and several treatment variables. Potential dependent functions were literacy, expressive language, and speech-in-noise recognition.
Results: Children with cochlear implants showed deficits in storage and processing, similar in size to those at second grade. Predictors of verbal working memory differed across groups: Phonological awareness explained the most variance in children with normal hearing; vocabulary explained the most variance in children with cochlear implants. Treatment variables explained little of the variance. Where potentially dependent functions were concerned, verbal working memory accounted for little variance once the variance explained by other predictors was removed.
Conclusions: The verbal working memory deficits of children with cochlear implants arise due to signal degradation, which limits their abilities to acquire phonological awareness. That hinders their abilities to store items using a phonological code.

It might seem that the relationship between the development of an assistive auditory device and the communication sciences would be in one direction only: The science would inform the development of that device. When it comes to the development of the cochlear implant (CI), however, the direction of this relationship has been bidirectional. Research with the multichannel CI has sparked some remarkable discoveries regarding how the auditory system functions and how that functioning is related to linguistic and cognitive processes. One of these discoveries has been that the amount and quality of auditory experience an individual receives can significantly influence the development and continued integrity of cognitive capacities. Previously, it was known that cognitive processes could affect the way that sensory information was interpreted, as in top-down linguistic context effects (e.g., Hirsh, Reynolds, & Joseph, 1954; Miller, Heise, & Lichton, 1951; Pollack, Rubenstein, & Decker, 1959), but those accounts never proposed that cognition affected the very nature of the sensory experience. Rather, it was thought that application of a cognitive construct—knowledge of linguistic structures—could affect the amount of sensory information needed to recognize speech, with less sensory information required to recognize what was said when strong linguistic constraints were in place. Furthermore, the effect was not presumed to operate in the other direction; the nature of the sensory input was never thought to affect cognitive operations. Instead, the neural representation of sound was presumed to travel from periphery to cortex, to be interpreted by cognitive and linguistic operations, without exerting an influence on those central operations.

With CIs came a new realization regarding the interaction of sensory and cognitive systems: Sensory experiences fundamentally affect cognitive operations (e.g., Harrison Bush, Lister, Lin, Betz, & Edwards, 2015). In particular, the amount and nature of auditory input after receiving a CI affects the encoding and processing of verbal material in working memory, especially for children (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2004). Children with hearing loss who receive CIs display diminished working memory capacities compared to their peers with normal hearing (NH), and these diminished capacities appear to affect

---

[a]The University of Florida, Gainesville

Correspondence to Susan Nittrouer: snittrouer@ufl.edu

Amanda Caldwell-Tarr is now at Comprehensive Health Insights, Louisville, KY.

Keri E. Low is now at Capital Region Medical Center, Jefferson City, MO.

Editor-in-Chief: Frederick (Erick) Gallun
Editor: Matthew Fitzgerald

Received December 30, 2016
Revision received March 29, 2017
Accepted July 3, 2017
https://doi.org/10.1044/2017_JSLHR-H-16-0474

Disclosure: *The authors have declared that no competing interests existed at the time of publication.*

other linguistic functions. The overarching goal of the study reported here was to further explore working memory capacities—specifically for verbal material—in children who get CIs.

Models of Verbal Working Memory

Investigators and clinicians agree on a broad definition of working memory: It is a mechanism by which information is placed in a temporary store to be used in further processing. An example of this capacity would be mental arithmetic, in which instructions and numbers need to be stored so that the problem can be solved. But beyond that, models of working memory differ in several ways, depending on proposed architecture and assessment methods. Single-component models view both storage and processing as elements of one global cognitive capacity (e.g., Just & Carpenter, 1992). Working memory is often assessed according to this model with a span test, in which a participant is asked to read or listen to a series of sentences and make a judgment regarding each one in turn, such as whether it is true or not (e.g., Reinhart & Souza, 2016; Souza & Arehart, 2015). After a set of sentences has been presented, the participant is then asked to recall as many first or last words as possible from each sentence, in any order. Span is determined by the number of sentences for which the participant can recall the specified words. These tasks assess how well an individual can retain words in memory in the face of significant, ongoing processing demands. Several linguistic and cognitive factors affect this measure, including syntactic comprehension.

Dual-component models of working memory posit that a central executive controls operations, including processing of stored items, but a separate front end is responsible for depositing information into storage (e.g., Baddeley, 2000). Where verbal material is concerned that front end is modeled as a phonological loop that recognizes phonological structure—especially phonemic—and uses it to encode items into the memory buffer. Working memory capacity according to this model can be assessed by asking participants to recall a string of unrelated items, as either free or order (serial) recall. These tasks were originally developed to examine the way that language is coded into a memory buffer (Campbell & Dodd, 1980; Campbell, Dodd, & Brasher, 1983; Spoehr & Corin, 1978), and they remain an especially sensitive test of storage, independent of processing. It is this second model of working memory that formed the basis of analyses reported here.

Verbal Working Memory in Children With CIs

Several hypotheses have been offered to explain the diminished verbal working memory capacities of children with CIs. First, the *auditory scaffolding hypothesis* suggests that the auditory sense is inherently and uniquely designed to handle temporal and sequential patterns. Young children learn to process these patterns through early auditory experiences, and any delay in obtaining those experiences will delay the acquisition of these sequential functions, leading to difficulties in language abilities because of their dependence on sequential patterns (Conway & Christiansen, 2005; Conway, Pisoni, & Kronenberger, 2009). According to this account, the primary source of the difficulty is the period of auditory deprivation early in life, before CIs are received. In turn, these problems in basic sequential processing skills are held responsible for deficits observed in children with hearing loss on a wide array of language-related abilities, including word recognition and syntactic parsing and comprehension (Pisoni, Kronenberger, Chandramouli, & Conway, 2016). For example, Kronenberger, Colson, Henning, and Pisoni (2014) explored the effects of working memory on latent measures of (a) language abilities, derived from standardized scores on tests of language and receptive vocabulary, and (b) speech recognition abilities, derived from measures of word and sentence recognition in noise. Their results showed that verbal working memory accounted for a significant amount of variability in language functioning for both children with NH and those with CIs and for a significant amount of variability in speech recognition in noise for children with CIs. This account places the locus of deficit in the cognitive domain, rather than the sensory.

Another account of the deficit in verbal working memory observed for children with CIs might be termed the *phonological bottleneck hypothesis*. This term, taken from early work on verbal working memory in children with dyslexia (Bar-Shalom, Crain, & Shankweiler, 1993; Crain, 1989; Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990; Hall, Wilson, Humphreys, Tinzman, & Bowyer, 1983; Mann & Liberman, 1984; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979), suggests that the working memory deficits encountered by children with CIs arise primarily because of poor phonological awareness. The term *phonological awareness* refers to the recognition of several layers of structure in the language we hear and read, including syllables, onsets and rimes, and individual phonemes. The last of these is most pertinent to the focus of this work, which is verbal working memory. Children with CIs have been found to have phonological deficits that are disproportionately large compared to any deficit they exhibit for lexical and syntactic skills (e.g., Nittrouer, Sansom, Low, Rice, & Caldwell-Tarr, 2014). For example, Nittrouer, Lowenstein, and Holloman (2016) reported latent phonological and lexicosyntactic abilities for second-grade children with NH and for children with CIs. Mean scores for the children with CIs were roughly 1 standard deviation below mean scores for children with NH on the latent measures of lexical and syntactic skills, but mean scores for phonological skills were 2 standard deviations lower. This disproportionately large phonological deficit has been observed by others (Ambrose, Fey, & Isenberg, 2012; James et al., 2005; Spencer & Tomblin, 2009) and is believed to be the result of the degraded auditory representations upon which they must rely due to processing limitations of CIs and the spread of excitation along the basilar membrane. And this degradation is greatest in the spectral domain. Thus, it has been shown that children with CIs demonstrate similar sensitivity to their peers with NH for temporal and amplitude cues to phonemic categories (Nittrouer, Caldwell-Tarr, Moberly, & Lowenstein, 2014; Nittrouer & Lowenstein, 2015) but greatly diminished sensitivity to spectral cues (Nittrouer, Caldwell-Tarr, et al., 2014). Appealing to a dual-processing model of verbal working memory (Baddeley, 1992, 2007; Baddeley & Hitch, 1974), Nittrouer, Caldwell-Tarr, and Lowenstein (2013) suggested that this poor sensitivity to spectral structure would curtail abilities of children with CIs to use phonological codes to store verbal material in a short-term memory buffer. This suggestion received support from that study on second-grade children with NH or with CIs: Although the children with CIs showed poorer recall than their peers with NH for order of words in closed-set lists, their response times were not as dissimilar. The poorer recall of serial order was taken to indicate deficits in how well the items were stored; speed of recall was taken to index how well processing of those items was implemented, regardless of the quality of the representations. According to this account, the primary source of diminished verbal working memory capacity in children with CIs is sensory, having to do with signal degradation.

Phonological Awareness, Verbal Working Memory, and Reading

The suggestion that poor phonological awareness constrains the abilities of children with CIs to store lexical items in short-term memory buffers with optimally durable codes is supported by outcomes of studies with children who have dyslexia. These children demonstrate diminished sensitivity to—or awareness of—phonological structure so frequently that the suggestion is commonly made that dyslexia has at its source a core phonological deficit (Ramus et al., 2003; Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Children with dyslexia also show deficits in recall of serial order for lists of words from closed sets (Katz, Shankweiler, & Liberman, 1981; Mann & Liberman, 1984; Nittrouer & Miller, 1999); however, their abilities to recall order for closed sets of serially presented nonverbal sounds is similar to that of children without dyslexia (Brady, Shankweiler, & Mann, 1983). Thus, the deficit in verbal working memory can be attributed directly to the phonological deficit they so commonly exhibit, the same deficit that accounts for their reading disabilities.

The existence of a common source of deficit—poor phonological awareness—underlying the reading and verbal working memory problems of children with NH who have dyslexia supports another hypothesis regarding children with CIs. Children with CIs are often found to have reading abilities poorer than those of their peers with NH, and that disability has been found to correlate with their verbal working memory problems (Bharadwaj, Maricle, Green, & Allman, 2015; Daza, Phillips-Silver, del Mar Ruiz-Cuadra, & López-López, 2014; Edwards, Aitkenhead, & Langdon, 2016; Fagan, Pisoni, Horn, & Dillon, 2007). This observed relationship has led to the conclusion that working memory capacity explains variability in reading ability among deaf children. However, these studies have not investigated phonological awareness to the same extent as verbal working memory, so it is difficult to ascertain whether one skill—sensitivity to phonological structure—underlies both reading and verbal working memory problems for these children, or if working memory capacity is independently responsible for variability in reading outcomes. A specific goal of the current study was to examine this additional skill of phonological awareness, and procedures were designed to evaluate whether phonological awareness and verbal working memory are independent sources of variability in the reading abilities of children with CIs. Language skills and speech recognition were also examined, as Kronenberger and colleagues (2014) had done.

Current Study

The discussion above highlights two areas of continued uncertainty surrounding potential relationships among childhood hearing loss, verbal working memory, and other language functions, including reading. These areas of uncertainty serve as the motivation for this report. The first area concerns what the deficits might be that underlie verbal working memory problems in children with hearing loss. Although all investigators hold hearing loss responsible for those problems, two hypotheses are offered concerning the nature of the effect: (a) The period of auditory deprivation may inhibit children's acquisition of sequential pattern recognition. (b) The degraded signal associated with hearing loss may interfere with their abilities to acquire the refined phonological representations needed to encode verbal material into a memory buffer. The first hypothesis should interfere more with the processing of material in a memory buffer; the second should interfere with storage. These are not mutually exclusive hypotheses, and both are explored in the work reported here.

The second area of uncertainty highlighted in the discussion above concerns the relationship between verbal working memory capacities and other language functions. It may be that variability in verbal working memory capacity among children with hearing loss accounts for most of the variability in speech recognition, language, and reading outcomes, or it may be that a common deficit—such as poor phonological sensitivity—underlies outcomes on all these language-related functions, either in addition to or instead of working memory capacities. This report sought to address both of these issues.

This report is divided into three parts, each with a separate objective. In the first part of the report, verbal working memory skills are examined in fourth-grade children with either NH or hearing loss severe enough to warrant CIs, with the goal simply being to see if there are differences between the two groups at this age. The children whose data are reported here were all part of a longitudinal study (e.g., Nittrouer, 2010; Nittrouer, Caldwell, & Holloman, 2012; Nittrouer, Lowenstein, & Holloman, 2016), and the verbal working memory abilities of these children have already been reported for a younger age (Nittrouer et al., 2013). Consequently, it was possible in this current study to examine the developmental trajectory of these skills to see if verbal working memory capacities appear to be improving for these children (relative to that of their peers with NH), declining further, or remaining impaired by a consistent amount over time. Results of the earlier study revealed that children with CIs were less accurate than children with NH when it came to serial recall for lists of words and that recall accuracy was moderately correlated with phonological awareness for children in both groups. Moderate correlations were also observed between recall accuracy and vocabulary abilities, but only for the children with CIs. This outcome could reflect delays for children with CIs in what is commonly termed lexical restructuring. This term refers to the view that children's earliest lexical entries are global in form, meaning they are not structured phonologically. Gradually, as more entries are added, these early lexical forms come to be analyzed into word-internal phonological units, and new entries are entered as such (e.g., Walley, Metsala, & Garlock, 2003; Walley, Smith, & Jusczyk, 1986). If children with hearing loss, especially those with CIs, experience signal degradation that makes it hard to recover phonological structure in the speech they hear, lexical restructuring may be highly restricted for them. Thus, these children may be obliged to use structures more global in nature to code words into a working memory buffer later into childhood, a constraint that could delay the development of verbal working memory capacities.

Response times were also measured at second grade (Nittrouer et al., 2013) but were found to be similar for children with NH and those with CIs. That finding was taken as evidence that the processing of stored representations was no more demanding for children with CIs than for those with NH. Earlier work using these same serial recall tasks demonstrated that response times—corrected for speed of motor response—were slower for a group of participants for whom slowed processing would be predicted (i.e., older adults) and for a condition in which greater cognitive demands were present (Nittrouer, Lowenstein, Wucinich, & Moberly, 2016). Consequently, it was concluded that the verbal working memory problems exhibited by these children with CIs arose due to deficits in the storage of words in short-term memory buffers, but their abilities to process the information stored were largely unaffected.

It is within this first part of this report that the claims of the auditory scaffolding and phonological bottleneck hypotheses are tested. Two differences between these hypotheses will be examined. First, the auditory scaffolding hypothesis proposes that the main source of deficit in verbal working memory for children with CIs arises due to periods of auditory deprivation early in life, whereas the phonological bottleneck hypothesis proposes that the biggest source of difficulty arises due to the poor signal quality available to these children. Thus, this report will examine the extent to which performance is dependent on the length of time before implantation and on signal quality. The second difference between the two hypotheses concerns the exact nature of the deficit. The auditory scaffolding hypothesis suggests that the difficulty rests with sequencing abilities, presumably a processing phenomenon. The phonological bottleneck hypothesis suggests that the problem has to do with encoding materials into the short-term memory buffer, which is a problem of storage. The methods used in this study assessed operations of storage and processing independently.

In the second part of this report, potential sources of variability in verbal working memory at fourth grade are examined for children with NH and for those with CIs. It may be that the processes involved in storing words in a short-term memory buffer and recalling the order of those words differ for the two groups of children. In particular, if children with CIs have highly deficient phonological representations, it may be that they use something other than a phonological code for storing verbal material in a short-term memory buffer. In particular, they may need to store items using a coarser or broader kind of representation. In this second part of the report, phonological sensitivity and vocabulary knowledge are examined as potential predictors of both storage and processing in verbal working memory. Nonverbal cognitive abilities are also examined as potentially predictive of working memory capacities.

The objective of the third part of this study was to explore the other language and literacy skills that might be affected by verbal working memory deficits. Three skills are examined. First, the effects of verbal working memory on reading skills are examined, with both word reading and reading comprehension serving as dependent measures. It could be that working memory affects these literacy-related skills or that the phonological deficit anticipated to be observed for the children with CIs would be found to explain any working memory and literacy deficits that might be found. Second, the effects of verbal working memory abilities on speech recognition in noise are examined. The ease of language understanding model predicts that working memory capacity should explain a large amount of individual variability in speech recognition, especially under conditions of signal degradation (e.g., Rönnberg, 2003; Rönnberg et al., 2013). However, experiments providing support for that prediction have almost universally used reading or listening span tests as their metrics of working memory (e.g., Arehart, Souza, Baca, & Kates, 2013; Lunner, 2003; Rudner, Lunner, Behrens, Thorén, & Rönnberg, 2012), so factors other than storage and processing could affect outcomes (Füllgrabe & Rosen, 2016). Finally, the effects of verbal working memory on productive language abilities are examined in the current report, as Kronenberger et al. (2014) had done.

Method

Participants

Data are reported here for 93 children: 47 with NH and 46 with severe-to-profound hearing loss who wore CIs.

Three more children with CIs were additionally tested, but they were unable to recognize the rhyming words used in the working memory task, so their data were not included. All children had just completed fourth grade at the time of testing.

All children in this experiment were participants in an ongoing longitudinal study (Nittrouer, 2010). They had all been enrolled as infants, so they met the criteria for participation at that time. Specifically, no child was enrolled who had any condition (other than hearing loss) that on its own would be expected to negatively impact language learning. If such a condition was diagnosed for any child during the first few years of life—such as autism—the child was dismissed from the ongoing study. All children with CIs were identified before 2 years of age, except one; all were presumed to have had hearing loss from birth. All children, including those with CIs, had parents with NH and came from homes where only English was spoken to them. The children with CIs and their families began receiving intervention shortly after being identified with hearing loss. That intervention was provided by someone with a master's degree or higher in a discipline providing specialized training in how to work with children with hearing loss to promote spoken language. Intervention was provided at least once a week up to the age of 3 years. From 3 years of age until the start of school, these children were in preschool programs especially designed for children with hearing loss and attended 4 days a week on average. Since reaching school age, all children were fully mainstreamed in their home schools.

In this study, 45% of children with NH and 43% of children with CIs were male. Table 1 shows demographic information for all children and treatment information for children with CIs. Children were similar in age at the time of testing. Socioeconomic status across groups was similar. The metric used to make that assessment was one that has been used before, in which occupational status and highest educational level are ranked on scales from 1 to 8, from lowest to highest, for each parent in the home. These scores are multiplied together, for each parent, and the highest value obtained is used as the socioeconomic metric for the family (Nittrouer & Burton, 2005). The group difference shown in Table 1 was not statistically significant. Scores suggest that the average child in the study had at least one parent who had obtained a 4-year university degree.

All children had been given the Leiter International Performance Scale–Revised (Roid & Miller, 2002) 2 years earlier. This instrument provides a nonverbal assessment of cognitive functioning. In this study, four subtests were administered that form what is termed the "brief IQ." These subtests assess figure-ground perception, form completion, sequencing abilities, and repeated patterns. Scores on Table 1 show that performance across groups was similar.

Treatment variables for children with CIs show that most of these children were identified early and implanted early. Five children had preimplant, better ear pure-tone average (PTA) thresholds better than 80 dB hearing level, and an overlapping (but not identical) group of five children received their first CI after the age of 36 months. Preliminary analyses indicated that outcomes for these children were no different from those for children with poorer preimplant PTA thresholds or those who received their implants earlier. Consequently, it was deemed appropriate to combine data for all children with CIs.

Children with NH were administered hearing screenings of the octave frequencies between 250 Hz and 8 kHz at 20 dB hearing level, and all passed. Regarding children with CIs, mean better ear, aided PTA threshold at the time of testing for these children was at 24 dB (8 dB) hearing level. Twenty-one of the children with CIs had at least 1 year of experience wearing a hearing aid on the ear contralateral to the ear that received the first CI (i.e., bimodal experience) at the time of receiving that first CI, and 14 of those children eventually received a second CI. In fact, at the time of testing, 31 children wore two CIs. Five children with some bimodal experience stopped wearing a hearing aid before this testing occurred but did not receive a second CI. Two children with some bimodal experience were still using a hearing aid at the time of testing.

Table 1. Mean and median scores for demographic and audiometric measures at fourth grade for children with normal hearing (NH) and children with cochlear implants (CI).

Demographic or audiometric measure	NH (*n* = 47)				CI (*n* = 46)			
	Mean	Median	*SD*	Range	Mean	Median	*SD*	Range
Age at time of testing (months)	125	125	4	114–132	128	128	5	118–139
Socioeconomic status (out of 64)	35	36	13	12–64	32	32	11	12–56
Leiter brief IQ standard score	105	104	14	77–135	101	98	16	73–139
Age at identification (months)					6	4	7	0–28
Age at 1st implant (months)					20	14	14	8–66
Age at 2nd implant (months)					49	45	26	14–108
Preimplant better ear PTA (dB)					102	105	17	55–120

Note. Socioeconomic status is a two-factor index based on the occupation and education of the primary income earner in the household. Pure-tone averages (PTAs) are given in dB HL and are for the three speech frequencies of 500, 1000, and 2000 Hz. Thirty-one children received a second implant.

Equipment

The materials for the serial recall task were presented through a computer, with a Creative Labs Soundblaster soundcard. A Roland MA-12C powered speaker was used, placed 1 m in front of the child at 0° azimuth. Custom-written software controlled the audio and visual presentation of the serial recall stimuli. Computer graphics (presented at 200 × 200 pixels) on a 21-in. touchscreen monitor were used to represent each word, number, and letter. Responses were collected by having the child touch the pictures shown on the monitor in the order recalled.

For the phonemic awareness task, stimuli were presented in audiovisual format with the same soundcard and speaker as that used for the serial recall task. For the speech recognition in noise task, stimuli were presented in audio-only format with the same soundcard and speaker as that used for the serial recall task. All tasks, except for the serial recall task, were video–audio-recorded using a Sony HDR-XR550V video recorder, and the children wore Sony FM transmitters to ensure good sound quality on the recordings. Receivers for these FM systems were connected directly to the audio input of the video recorder.

General Procedure

All procedures were approved by the institutional review board at the Ohio State University. All stimuli were presented at 68 dB sound pressure level. Children came to the laboratory on 2 days, in groups of two to six children. They were administered a number of tasks in individual test sessions lasting no more than 1 hr each and were given breaks between sessions of no less than 1 hr each.

Part I: Verbal Working Memory

The goal of this first part of the report was to examine whether there continued to be, at fourth grade, differences in verbal working memory between children with NH and those with CIs who were all included in an earlier report (Nittrouer et al., 2013). Order recall was examined in this study, rather than free recall. In order—or serial—recall, the items to be recalled form a closed set, and the participants' task is just to recall the order in which they were presented. In free recall, items are not known ahead of time. Consequently, vocabulary size and structure are critical to outcomes. Order recall has been shown to be more sensitive to phonological awareness than free recall, at least for adults (Baddeley, Lewis, & Vallar, 1984; Burgess & Hitch, 1999; Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015). There is no reason to suspect that relationship would be different for children, and indeed, order recall accuracy has been found to correlate with phonological awareness in earlier studies with children with NH (Brady et al., 1983; Nittrouer et al., 2013). Stimuli and methods in the current study were designed to measure both storage and processing in verbal working memory. This task of immediate serial recall has been used extensively in the past, both to examine the nature of working memory for verbal materials (Campbell & Dodd, 1980; Campbell et al., 1983; Spoehr & Corin, 1978) and to examine whether children with dyslexia demonstrate working memory deficits that can be traced to their poor phonological representations (Katz et al., 1981; Mann & Liberman, 1984; Nittrouer & Miller, 1999). These studies have revealed consistent and stereotypical patterns of response to dynamically presented, verbal material, consisting of strong primacy and recency effects that are not observed for nonverbal material or even stationary verbal material, such as written words (e.g., Campbell & Dodd, 1980; Campbell et al., 1983; Shand & Klima, 1981). On the basis of the extensive data already collected with these methods, it is reasonable to conclude that they are valid measures of working memory for verbal materials. The methods have also been found to be reliable. For example, Nittrouer and Miller (1999) tested 11-year-old children with NH and typical language on two different days using two sets of the materials to be used in this study (but with two additional list items in that earlier work). The computed reliability coefficient was .75, which is considered adequate (Nunnally & Bernstein, 1994).

Stimuli and Procedure

Three sets of six stimuli each were used: nonrhyming nouns, rhyming nouns, and nonrhyming adjectives. These stimuli were used in testing with these children at second grade (Nittrouer et al., 2013), except that nonrhyming adjectives were not included at that time. The inclusion of nonrhyming and rhyming words allowed examination of the extent to which phonological codes were used for storage of items in the short-term memory buffer; more accurate recall should be observed for nonrhyming words if a phonological code is used. The inclusion of nouns and adjectives was done to assess processing of the stored items. In this task, children were required to respond by touching pictures on a computer monitor associated with each test item and were instructed to do so as quickly as possible. Pictures can more transparently represent nouns than adjectives; an inference must be made in the latter case, thus introducing a processing load. Response times were measured in this study. Earlier work with young and older adults has demonstrated slower response times for nonrhyming adjectives than for nonrhyming or rhyming nouns (Nittrouer, Lowenstein, Wucinich, & Moberly, 2016), reflecting that greater processing load.

All stimuli were recorded with sampling rates of 22.05 kHz, using 10-kHz low-pass filtering and 16-bit digitization. Word samples were spoken by a man who recorded five samples of each word in random order. The nonrhyming (NON) nouns were *ball, coat, dog, ham, pack,* and *rake*. The rhyming (RHY) nouns were *bat, cat, hat, mat, Pat* (represented by a picture of a woman), and *rat*. The nonrhyming adjectives (ADJ) were *big* (represented by a picture of a big dog next to a small dog), *deep* (a deep swimming pool), *full* (a full glass of water), *hot* (a steaming cup of coffee), *sad* (a crying child), and *wet* (a wet cat). One token of each word was selected from the larger recorded set for use in testing, so words would match each other closely in duration, fundamental frequency, and intonation. All were roughly 500 ms in length, had a fundamental frequency of 110 Hz, and had flat/falling intonation contours.

All words were selected to be nouns or adjectives that could as transparently as possible be represented with pictures. Although words could not be equated on frequency of occurrence because of the restrictions on list construction, children were familiarized with the words to be used before testing. In this way a priori probabilities of occurrence were equated.

Six nonrhyming letters (*F, H, Q, R, S, Y*) were used in practice. These were produced by the same talker who produced the word samples. The numerals *1* through *6* were also used for practice, but these were not presented auditorily, so digitized audio samples were not needed.

During this task, the experimenter always sat on the child's left. The monitor was positioned directly in front of the child. Children had to keep their hands flat on the table in front of the monitor during audio presentation. There could be no articulatory movement of any kind (voiced or silent) between hearing the items and touching the images. Testing in each condition consisted of 10 lists, and the software generated a new order for each list.

Baseline Response Time

The first task during testing was designed to collect a baseline of response time. Colored squares with the numerals *1* through *6* were displayed in a row in random order across the top of the monitor. The child was instructed to touch the numerals in order from left to right across the screen. The experimenter demonstrated one time, and then the child performed the task four times as practice. Children were instructed to touch the numbers as fast as they comfortably could. They were told to keep their hands flat on the table until the numbers appeared on the screen and not to talk or whisper until they were done with the task. After this practice, the child performed the task five times. From those five trials, a mean time was computed and was used to compare baseline response times across groups. Next, the child was instructed to touch the numbers in numerical order, as fast as they comfortably could. This was also performed five times and was done to provide practice touching images in an order other than left to right.

Training and Pretest

The next task was practice with the test procedures using the letter strings. The images of the letters appeared in random order across the top of the monitor, and then the list of letters was presented over the speaker in an order different from the one shown, at a rate of one per second. The experimenter demonstrated how to touch each image in the order heard as quickly as possible. The child was then provided with two practice trials. Feedback regarding accuracy of recall was not provided, but children were reminded, if need be, to keep their hands on the table during stimulus presentation and to refrain from any articulatory movements until after the reordering task was completed.

The experimenter then moved to the first stimulus type to be used in testing and made sure the child recognized each item. To do this, all images were displayed on the screen, and the words were played one at a time over the speaker. After each word was played, the experimenter touched the correct image. The software then displayed the images in a different order and again played each word one at a time. This time the child needed to touch the correct image after each word was played. Feedback was provided if an error was made on the first round. On a second round of presentation, children were required to select all images without error. No feedback was provided this time. If a child made an error on any item, that child did not proceed to testing for that list. This pretest was designed to make sure children recognized each item and was given just prior to testing with each of the three stimulus sets.

Testing and Posttest

Testing with each set of items took place immediately after the pretest with those items. Testing consisted of 10 lists, and stimuli were presented at a rate of one per second. Pictures representing the words appeared across the top of the monitor before the stimuli were played. After the list items were heard, children touched the pictures in the order recalled. As each image was touched, it dropped to the vertical middle of the monitor, into the next position going from left to right. The order of pictures could not subsequently be changed. After testing with each stimulus type, a posttest identical to the pretest was given to ensure that children had maintained correct associations between images and words through testing. If a child was unable to match even one word to the corresponding image, that child's data were not included in the analyses.

Scoring

The software recorded both the order of presentation and the child's recall of those orders. It then compared the order of words recalled in each position for each list to the word orders actually presented. A word was considered wrong if it was recalled in the wrong list position. The total number of errors across list positions and lists was computed. Scores for each condition were transformed into percent correct scores by multiplying the proportion of correct responses by 100. That value was used to index accuracy. The software also recorded the time between the end of presentation of the last word and the selection of the last word in responding. It computed the mean time across the 10 lists within the condition.

Results

All six measures reported in this section—three measures of accuracy and three of response time—were examined for normal distributions and homogeneity of variances, and all were found to meet these assumptions. An alpha of .05 was used in these analyses, although p values of < .10

are reported. When $p > .10$, outcomes are described simply as not significant.

Recall Accuracy

Figure 1 shows mean percent correct for each position in each condition for children with NH and for those with CIs. A three-way, repeated-measures analysis of variance (ANOVA) was performed on these data, with condition and position as within-subject, repeated-measures factors and group as the between-subjects factor. The two within-subject factors were significant: condition, $F(2, 182) = 41.04$, $p < .001$, $\eta^2 = .311$, and position, $F(5, 455) = 207.89$, $p < .001$, $\eta^2 = .696$. Regarding the condition effect, it can be seen in Figure 1 that children in both groups were more accurate for NON, followed closely by ADJ, and finally by RHY. Regarding the position effect, responses show both primacy effects, with better accuracy for early list positions, and recency effects, with better accuracy for the last position. The Condition × Position interaction was also significant, $F(10, 910) = 2.157$, $p = .018$, $\eta^2 = .023$. This interaction was not strong, but appears to be due to slightly weaker recency effects for ADJ.

The main effect of group was also significant, $F(1, 91) = 21.59$, $p < .001$, $\eta^2 = .192$, indicating that children with CIs were less accurate in recalling order. In addition, the Position × Group interaction was significant, $F(5, 455) = 3.01$, $p = .011$, $\eta^2 = .032$. This effect appears to be due to children with CIs showing steeper drops in performance near the beginnings of lists than children with NH. Nonetheless, this effect was not strong, so results were collapsed across positions, and mean accuracy for list conditions was used in future analyses.

Figure 2 shows mean recall accuracy for each condition collapsed across positions for children with NH and those with CIs. This figure highlights that performance was best for the NON condition and is diminished only slightly for the ADJ condition. However, it is much poorer for the RHY condition. Children with CIs performed more poorly overall than children with NH, although the pattern across conditions was similar for both groups. Paired *t* tests showed that accuracy of responding in every condition was significantly different from that of every other condition: NON versus RHY, $t(92) = 8.19$, $p < .001$; NON versus ADJ, $t(92) = 2.12$, $p = .037$; and ADJ versus RHY, $t(92) = 7.02$, $p < .001$.

Second-Grade Comparison

These scores at fourth grade were compared to those from second grade. Means across the two grade levels are shown in Figure 3 for the NON and RHY conditions. The ADJ condition was not included in testing in second grade, so that the condition is not shown. In second grade, one child in each group was unable to reliably match the words to the pictures for the NON condition; two children with NH and 13 children with CIs were unable to do that matching reliably for the RHY condition. Consequently, sample sizes are slightly smaller for these second-grade data. A three-way, repeated-measures ANOVA was performed on the data shown in Figure 3, with grade and condition as within-subject factors and group as the between-subjects factor. Both within-subject main effects were significant: grade, $F(1, 76) = 75.73$, $p < .001$, $\eta^2 = .499$, and condition, $F(1, 76) = 56.48$, $p < .001$, $\eta^2 = .426$. The main effect of group was also significant, $F(1, 76) = 14.13$, $p < .001$, $\eta^2 = .157$. None of the interactions were significant. Thus, mean

Figure 1. Mean percent correct recall for the verbal working memory task by position and condition for children with normal hearing (NH) and children with cochlear implants (CI) at fourth grade.

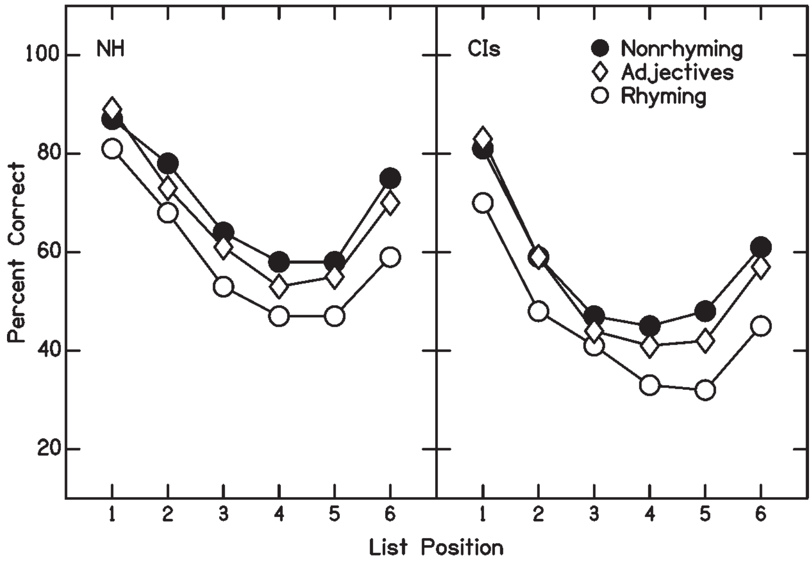
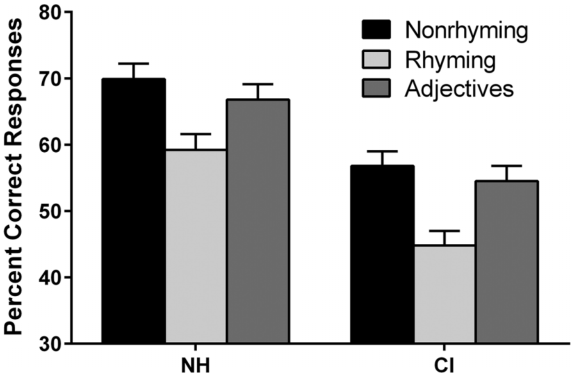


Figure 2. Mean percent correct recall for the verbal working memory task collapsed across position for each condition for children with normal hearing (NH) and children with cochlear implants (CI) at fourth grade.



scores for both groups improved across grade level, and scores were better for the NON condition than for the RHY condition at both grade levels. Children with NH performed better than children with CIs at both grade levels. However, these main effects remained stable across grade levels. Figure 3 illustrates that performance of children with CIs at fourth grade was similar to that of children with NH at second grade, suggesting that the development of verbal working memory for these children with CIs was typical in trajectory but delayed by 2 years.

Treatment Effects

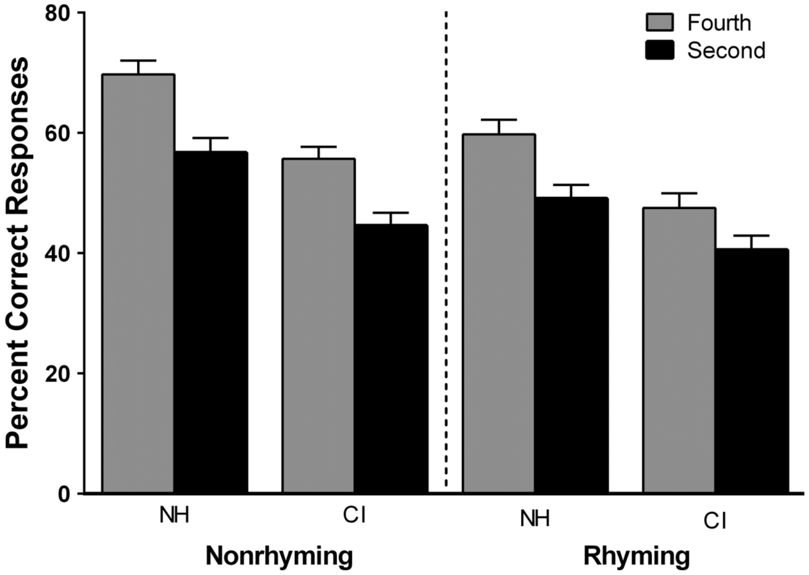
The effects of treatment variables on outcomes for children with CIs at fourth grade were examined. First, mean percent correct across the three stimulus conditions was used as a dependent measure in regression analysis, which was appropriate because there was no Condition × Group interaction. Age of identification, age of first CI, preimplant better ear PTA, and aided PTA were each included as a predictor in a separate analysis. None of these four variables were found to explain a significant amount of variance in recall accuracy.

Next, two *t* tests were conducted on mean percent correct scores, using number of CIs (one or two) and whether or not the child had some bimodal experience at the time of receiving a first CI as grouping factors. Neither effect was significant, although the bimodal effect was close, $t(44) = 1.757$, $p = .086$, reflecting a trend of slightly better performance for children with some bimodal experience at the time of receiving a first implant than for children with no bimodal experience: 56% correct serial recall (15%) for children with some bimodal experience versus 49% correct (11%) for children with no bimodal experience.

Response Times

The first measure examined involved the baseline response times to see if children in the two groups differed in the time it took to touch six pictures from left to right. Mean baseline response times were 2.1 s (0.4 s) for children with NH and 2.2 s (0.5 s) for children with CIs. This difference was not statistically significant. Thus, it was concluded that children in the two groups did not differ in the time it took them to touch pictures from left to right, so mean response times in each condition were used as dependent measures in further analyses, without correcting for baseline times. These mean response times for each

Figure 3. Mean percent correct recall for the verbal working memory task for each condition presented in second and fourth grade for children with normal hearing (NH) and children with cochlear implants (CI).



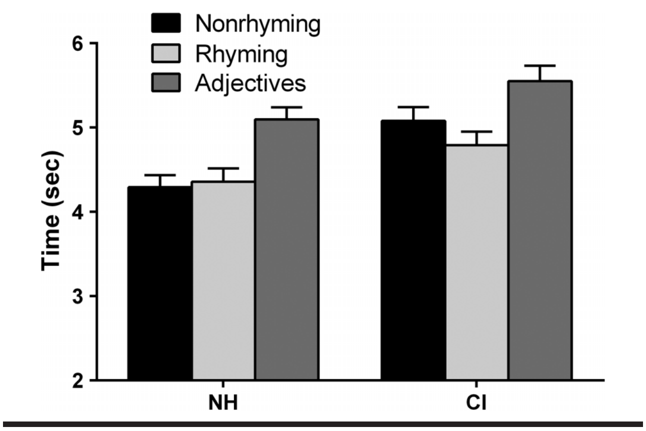
condition are shown in Figure 4. Different patterns across conditions seem to be present for each group. Children with NH showed similar response times for the NON and RHY conditions and longer response times for the ADJ condition. Children with CIs showed a similar difference between the NON and ADJ conditions but were somewhat faster for the RHY condition. Overall, it appears that children with CIs were slower than children with NH.

A two-way, repeated-measures ANOVA was performed on these data, with condition as the within-subject, repeated measure and group as the between-subjects measure. Both main effects were significant: condition, *F*(2, 182) = 23.54, $p < .001$, $\eta^2 = .205$, and group, *F*(1, 91) = 9.80, $p = .002$, $\eta^2 = .097$. However, the Condition × Group interaction was not significant, so it must be concluded that children with CIs were generally slower than children with NH, but children in the two groups had similar differences in response times across conditions. Paired *t* tests showed that response times were not significantly different for NON and RHY, but each of those conditions was significantly different from ADJ: ADJ versus NON, *t*(92) = 5.07, $p < .001$, and ADJ versus RHY, *t*(92) = 5.97, $p < .001$. These outcomes match predictions, and it is concluded that response times for NON and RHY are not significantly different.

Second-Grade Comparison

A three-way, repeated-measures ANOVA performed on response times in second and fourth grade resulted in significant main effects of grade, *F*(1, 76) = 16.07, $p < .001$, $\eta^2 = .175$, and group, *F*(1, 76) = 9.58, $p = .003$, $\eta^2 = .112$. The main effect of condition was not significant, and there were no two-way interactions. However, there was a significant three-way interaction for Grade × Condition × Group, *F*(1, 76) = 4.73, $p = .033$, $\eta^2 = .059$. That interaction likely arose due to the slightly faster response times to the stimuli in the RHY condition shown by children with CIs at fourth grade. Thus, these analyses mainly show that children with CIs were slower than children with NH, as was found when the fourth-grade outcomes were examined alone. These across-grade results also indicate that children in both groups generally became faster between second and fourth grade.

Figure 4. Mean response time for each condition for children with normal hearing (NH) and children with cochlear implants (CI) at fourth grade.



The finding of a significant group effect across grades, with no Grade × Group interaction, needs further explanation. A significant group effect for response times was not observed for these children at second grade, *F*(1, 81) = 2.90, $p = .093$, $\eta^2 = .035$ (Nittrouer et al., 2013), but was at fourth grade. Typically, this would predict that a significant interaction term would be found. In this case, however, it appears that the change in response times across groups was just enough to evoke a significant main effect of group at fourth grade, but not a significant interaction. Children with NH increased their response times by slightly more than the children with CIs: Cohen's *d* for the difference in response times from second to fourth grade was 0.43 for children with NH and 0.36 for children with CIs.

Overall, these results show that the children with CIs were slower at processing than the children with NH. That finding in turn led to the question of whether the group difference observed for accuracy of responding could be attributable to this difference in response times: If it takes longer to respond, the stored representation has more time to decay. Consequently, the two-way, repeated-measures ANOVA reported first on recall accuracy (in fourth grade only) was run again, using mean response time across the three conditions as a covariate. The main effect of condition was still significant, *F*(2, 180) = 3.58, $p = .030$, but effect size was reduced from $\eta^2 = .311$ to $\eta^2 = .038$. The main effect of group was also still significant, *F*(1, 90) = 14.73, $p < .001$. In this case, effect size was reduced by far less, from $\eta^2 = .194$ to $\eta^2 = .141$, prompting the conclusion that response times did not explain group differences in recall accuracy.

Treatment Effects

The same treatment variables were evaluated for potential effects on response time as those evaluated for effects on recall accuracy. However, no significant effects were observed. Of particular note, neither the age of identification nor the age of receiving a first CI predicted response times. Furthermore, mean response times were identical for children with CIs who had some bimodal experience and those who did not.

Discussion

The analyses presented here support several main conclusions. First, children in both groups were more accurate in their recall of serial order when words did not rhyme than when they rhymed. This finding matches previous outcomes for children and adults and suggests that the nonrhyming words can be coded into a short-term memory buffer with more salient and stable structure. Generally, the form of that structure is presumed to be phonological in nature, and that appears to be the case for the children with NH. However, for the children with CIs, it is not clear whether or not that was the case. In addition, response time—which was used in this experiment as a metric of processing effort—was longer when the pictures representing the words were less transparently related (i.e., the ADJ condition), so an inference needed to be made. That finding supports the validity of using response time as a metric of cognitive effort.

Regarding differences between groups, children with CIs demonstrated both poorer recall of serial order and slower response times. At fourth grade, Cohen's *d* for the group effect was 0.96 for recall accuracy and 0.65 for response time. Thus, it required more cognitive effort to do the processing involved in this serial recall task for the children with CIs, and they were less accurate at doing so. However, the increased effort required by children with CIs could not explain their poorer recall, an important finding because it means that another explanation must be found for that poor recall.

Some insight into the source of diminished performance for children with CIs can be gathered from the investigation into the predictive value of the treatment factors. First, no effects related to duration of auditory deprivation were found for either recall accuracy or response time. That lack of effect appears to contest the auditory scaffolding hypothesis, which suggests that it is the early period of auditory deprivation that accounts for deficits in sequential processing abilities. Accordingly, it could be predicted that the amount of deficit would be explained by the length of deprivation. That was not found. Of course, an alternative explanation might be that all the children with CIs had sequential processing deficits of similar magnitude, which could be the case if there is a critical period for developing those sequential processing skills, and these children had all passed that period before getting CIs.

A marginal effect of having had a period with bimodal stimulation was found for recall accuracy, but not response time. If this trend represents a real effect, it could support the suggestion that the highly degraded signal available to children with CIs accounts for their diminished verbal working memory capacities. Children who had a period with bimodal stimulation—arguably a richer signal for these children—may have had the opportunity to either acquire better phonological awareness or, at least, develop somewhat richer lexical representations, even if those representations were not phonological in structure. However, at the time of testing, few of these children were using hearing aids with their CIs. Consequently, the bimodal group did not have better spectral resolution at the time. Any beneficial effects would have had to come in the form of having had a chance to acquire more refined representations early in life.

Part II: Potential Sources of Variability

The goal of this part of the report was to evaluate potential sources of variability in verbal working memory for children with NH and those with CIs. Three measures were considered as potential predictor variables in regression analyses, each for a specific reason. First, phonological awareness was examined as a potential predictor variable, because the dual-component model of working memory served as the basis of this investigation. That model explicitly posits a phonological loop as being responsible for how items are coded into the memory buffer. One hypothesis examined here was that diminished sensitivity to phonological structure arising from degraded signals would impair the operations of the phonological loop for children with CIs. Thus, group differences in phonological awareness might account for any group differences observed in verbal working memory capacity. Second, vocabulary skills served as a second potential predictor of verbal working memory, because if children with CIs lack sensitivity to phonological structure, they may need to use broader lexical structure to store words in a memory buffer: The phonological loop may more appropriately function as a "lexical" loop for these children. Finally, nonverbal cognitive abilities were examined as potential predictors of verbal working memory capacity, because it may simply be that verbal working memory capacity is entirely explained by general cognitive capacities.

Stimuli and Procedure

Phonological awareness was assessed with the final consonant choice task (e.g., Nittrouer & Lowenstein, 2015). In this task, audiovisual presentation is used in which children can see and hear the talker. First, they are presented with the target word, which they must repeat correctly. They are given three chances to do so. If they do not, they are not tested on that word. However, it was extremely rare that any of the children in this study were unable to recognize words presented in this manner. After repeating the target, three word choices were presented, again in audiovisual modality. The task was to select the word that ended in the same sound as the target. There are 48 trials in this task, and they are organized with increasing difficulty. If the child responds incorrectly on six consecutive trials, ceiling is reached so testing is discontinued. Percent correct scores were used in analyses. Scoring was done by the experimenter at the time of testing, but another member of the laboratory staff watched all videos and confirmed all scores.

Vocabulary skills were measured with the Expressive One-Word Picture Vocabulary Test–Third Edition (Brownell, 2000). A measure of expressive vocabulary knowledge was selected over one of receptive vocabulary knowledge, because it assesses a deeper level of word familiarity. An individual may be sufficiently familiar with a word to select the picture out of a set of four that best matches that word when it is heard, but it takes a deeper familiarity to retrieve that word from one's own lexicon when shown a picture. In this particular task, children are shown pictures one at a time and asked to produce the name of each picture. Ceiling is reached when the child misses six consecutive items. Scoring was done at the time of testing, but another member of the laboratory staff watched all videos and confirmed all scoring. This measure is well standardized, and standard scores were used in analyses.

For the metric of nonverbal, cognitive abilities, standard scores across the four subtests of the Leiter International Performance Scale–Revised (Roid & Miller, 2002) forming the brief IQ measure were used. This task and outcomes were discussed in the Participants section. No group difference was observed for this measure.

Results

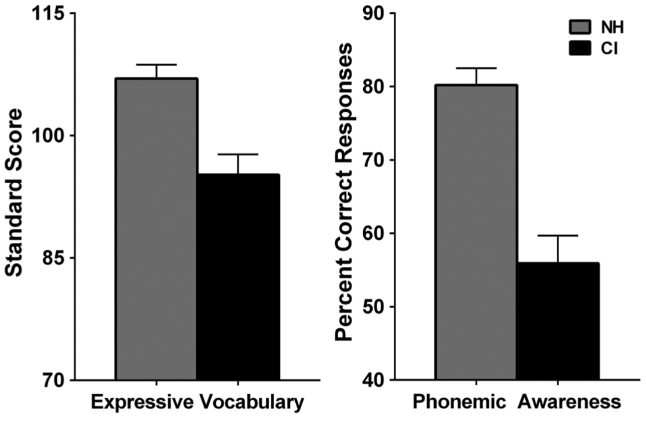
The three potential predictor variables were examined to see if they met criteria for normal distributions and homogeneity of variance. The measure of phonological awareness, final consonant choice, was the only one not found to meet these requirements. It was negatively skewed, so arcsine transformations were applied. Those transformations met the requirement of having a normal distribution and thus were used in further analyses. Bivariate correlations computed between each pair of these three measures for children with NH and those with CIs separately revealed two significant correlations, both for children with CIs: vocabulary versus brief IQ, $r = .332$, $p = .024$, and vocabulary versus phonological awareness, $r = .436$, $p = .002$.

Figure 5 shows mean scores for expressive vocabulary and phonological awareness. The figure reveals strong group effects for these additional measures, and indeed, both showed statistically significant effects: vocabulary, $t(91) = 3.93$, $p < .001$, and phonological awareness, $t(91) = 5.44$, $p < .001$. Next, the three measures were used in regression analyses.

Recall Accuracy

First, potential predictors of recall accuracy were examined separately. For this purpose, individual mean percent correct scores across the three stimulus conditions were used as the dependent variable, and each of the additional three measures described above was used as a potential predictor variable in a separate regression analysis. Table 2 shows standardized (β) coefficients for children with NH and for children with CIs separately. These standardized coefficients are equivalent to Pearson product–moment correlation coefficients when computed for two variables. For children with NH, the only measure found to be a significant predictor of recall accuracy was phonological awareness. For children with CIs, all three measures were significant predictors, but of these, expressive vocabulary was the strongest. Because all three measures were significant predictors, a stepwise regression was done to examine how they interacted, and once the variability explained by vocabulary was accounted for, neither of the other factors explained any additional variability in recall accuracy for these children with CIs.

Figure 5. Mean standard scores for expressive vocabulary and percent correct scores for phonemic awareness for children with normal hearing (NH) and children with cochlear implants (CI) at fourth grade.



The finding that sensitivity to phonological structure explains much of the variability in verbal working memory capacity for children with NH is compatible with the dual-component model of working memory adopted in this work, because the model explicitly suggests that there is a front end that recovers and uses phonological structure for storage in the memory buffer. It is somewhat challenging, however, to propose that vocabulary skills account for variability in verbal working memory capacity for children with CIs, because that is not the level of linguistic structure postulated as being used for storage in the dual-component model. Furthermore, Kronenberger and colleagues (2014) contended that the direction of the relationship was opposite to that suggested here, with working memory supporting the acquisition of vocabulary skills in their view.

In order to address this question of direction of relationship, a cross-lagged analysis was conducted with working memory and vocabulary scores from the children with CIs from second to fourth grade. This technique is used commonly to establish the direction of relationship among variables in developmental studies (e.g., Ritchie, Bates, & Plomin, 2015; Sperlich, Meixner, & Laubrock, 2016; Woynaroski, Yoder, & Watson, 2016). In its simplest form, it consists of computing a partial correlation coefficient between one proposed dependent measure and one proposed predictor variable, controlling for the variability in

Table 2. Standardized coefficients for each predictor variable, with mean recall accuracy across conditions used as the dependent variable, computed separately for children with normal hearing (NH) and children with cochlear implants (CI).

Group	Expressive vocabulary	Phonological awareness	Nonverbal IQ
NH	.015	**.539*****	.184
CI	**.616*****	**.403****	**.415****

Note. Significant coefficients are in bold.

$^{**}p < .01$. $^{***}p < .001$.

the proposed dependent measure associated with performance at an earlier age. Scores for the proposed predictor variable can be from the later or earlier age. For current purposes, verbal working memory and vocabulary scores at fourth grade were alternately set as the proposed dependent variable. Looking first at verbal working memory, scores for verbal working memory at second grade served as the covariate, and vocabulary skills at both second grade and fourth grade were then correlated with fourth-grade working memory performance. The Expressive One-Word Picture Vocabulary Test–Third Edition had been administered to these children at second grade. Mean scores were 110 (14) for children with NH and 93 (18) for children with CIs; this difference was significant, $t(89) = 5.08$, $p < .001$. In the cross-lagged analysis, vocabulary scores from both grades were significantly correlated with working memory performance at fourth grade: second-grade vocabulary scores, $r = .378$, $p = .011$, and fourth-grade vocabulary scores, $r = .476$, $p = .001$. Looking next at vocabulary scores as the potential dependent measure, neither second-grade nor fourth-grade performance on the working memory task accounted for any significant proportion of variability at fourth grade once second-grade vocabulary was controlled for. On the basis of this analysis, it is appropriate to conclude that vocabulary development was supporting the emergence of verbal working memory capacity, rather than the other way around.

Response Times

Next, potential predictors of response times were examined. In this case, individual mean times across the three stimulus conditions were used as the dependent variable, and the three potential predictor variables were included in separate analyses for children with NH and children with CIs. However, no significant effects emerged.

Finally, regression analyses were performed to see the extent to which response times predicted recall accuracy. No significant effects were observed for either children with NH or for children with CIs.

Discussion

The second part of this report examined factors that could be expected to explain verbal working memory capacity in children. It was revealed that variability in working memory performance was explained by different underlying skills, depending on whether children had NH or CIs. For children with NH, phonological awareness explained much of the variability in recall accuracy. That finding in combination with the independence observed between recall accuracy and response times is compatible with the dual-component model of verbal working memory described by Baddeley and colleagues (Baddeley, 1992, 2007; Baddeley & Hitch, 1974). These children appear to encode words into a memory buffer using the phonological loop, and that operation appears fairly independent of the processing component.

For children with CIs, recall accuracy was strongly dependent on vocabulary. This finding is interesting, because the task was a closed set. Children knew the six words that would be included in the recall task each time. Consequently, the relationship between vocabulary and recall accuracy could not simply reflect the size of children's lexicons, as would be expected with an open-set task. Instead, this strong relationship must reflect a similarity in the code with which words are stored in both short-term and long-term memory. For children with CIs, that code is apparently less segmental than the code used by children with NH. Thus, the conclusion that children with CIs store words in a short-term memory buffer using a different code compared with that of children with NH is reached. Whereas it seems appropriate to suggest that children with NH use a phonological code for storing words in a short-term memory buffer, children with CIs appear to use a more global lexical representation, which would be expected to be less efficient. Children in both groups appear to have a front-end processor responsible for extracting structure from the sensory input and using that structure to code items into a memory buffer: In one case, the structure extracted was specifically phonemic in nature; in the other case, the structure was more global.

Part III: Potential Dependent Functions

The last section of this report addressed the question of what language functions are supported by verbal working memory. The primary skill that has previously been identified as affected by verbal working memory in children with CIs is reading, although this function is variably defined across investigations as either word reading or reading comprehension. In this section, both aspects of reading are considered. Other skills identified as being affected by verbal working memory are language processes, broadly defined, and speech recognition. In this report, we operationally defined language processing as expressive and used skill at constructing oral narratives as the dependent measure. Speech recognition in noise was used as the dependent measure for evaluating recognition, because the ease of language understanding model suggests that working memory becomes especially important for speech recognition when the signal is degraded, such as by noise.

Stimuli and Procedure

Reading

The Qualitative Reading Inventory–Fourth Edition (Leslie & Caldwell, 2006) was used to assess word reading and reading comprehension. This instrument has both narrative and expository passages written at various levels of reading ability. The child reads a passage and retells it in as much detail as possible. Next, the examiner asks questions that the child must answer. For this study, two passages were selected: one narrative and one expository. Ten questions were asked after each story. All testing was audio–video-recorded, so scoring could be done later. Two members of the laboratory staff independently scored all word reading and answers to the comprehension questions. Scores of the staff members were compared for each child, and if they differed by more than 2% for word reading or by a single answer for the comprehension questions, the staff members reviewed the responses together to reach a consensus. Scores from the first scorer or combined scoring were used in the analyses. The percentage of words read correctly across the two stories was used as the dependent measure for word reading, and the percentage of questions across the two stories answered correctly was the dependent measure for reading comprehension.

Narrative Abilities

A narrative elicitation task was implemented using the picture sequences of Fey, Catts, Proctor-Williams, Tomblin, and Zhang (2004). There are four of these sequences, each consisting of four pictures. However, one of the sequences was always used to demonstrate to each child what was expected by having the experimenter tell a story. During testing, each child was first asked to select the picture sequence to be used for the narrative. Next, the examiner demonstrated a narrative story. Children were then given 5 min to plan their own narratives, which were audio–video-recorded upon presentation. These narratives were scored later by two staff members independently. There were 12 scoring categories, and between zero and three points could be obtained in each category, making 36 the maximum number of points obtainable. Laboratory staff trained with narratives from practice participants before scoring children in this study, but then two members of the laboratory staff independently scored narratives from children in this study. Reliability between the two scorers was .983, which was considered adequate. Scores from the first scorer were converted to percentages (of the total possible of 36 points) and used in analyses. Categories for scoring and criteria for each score are provided in the Appendix.

Speech Recognition in Noise

Five-word sentences from the Hearing-in-Noise Test (Nilsson, Soli, & Sullivan, 1994) were used. These were produced by a male talker. The long-term average spectrum of these sentences was computed and used to shape noise. Each sentence was embedded in a different stretch of noise, at each of two signal-to-noise ratios (SNRs): −3 dB and 0 dB. All children with CIs were presented with sentences at 0 dB; half of the children with NH were presented sentences at −3 dB, and half were presented sentences at 0 dB SNR. This split in SNR for children with NH was implemented due to conflicting interests in maintaining similar levels of signal degradation across groups, which would be achieved by using the same SNR, and maintaining similar recognition probabilities across groups, which would be achieved by using a better SNR for the children with CIs. In total, there were 60 sentences, but each child heard a random sample of 30 sentences. The child's task was to repeat the sentence after hearing it. Responses were audio–video-recorded for scoring later. One staff member scored responses from all children, and a second staff member scored responses from 10 children (five from children with NH and five from children with CIs) to obtain a metric of reliability. That reliability metric was obtained on a word-by-word basis. It was .985, which was considered adequate.

Results

The four dependent measures were examined to see if they met criteria for normal distributions and homogeneity of variance. The measure of word reading was the only one not found to meet these requirements. It was negatively skewed, so arcsine transformations were applied. Those transformations met the requirement of having a normal distribution, so they were used in further analyses. Bivariate correlations were computed between each pair of these four measures for children with NH and those with CIs separately. For children with NH, only the correlation between reading comprehension and narrative scores was significant, $r = .339$, $p = .020$. Speech recognition scores did not correlate significantly with any other measure, and that was the case for scores from both SNRs. For children with CIs, three of the correlations were significant: word reading and reading comprehension, $r = .649$, $p < .001$; word reading and narrative scores, $r = .496$, $p < .001$; and reading comprehension and narrative scores, $r = .613$, $p < .001$. Again, speech recognition scores did not correlate with any other measure.

Figure 6 shows mean responses for the measures of word reading, reading comprehension, and narrative scores. Group differences are obvious for all these measures, and all were significant: word reading, $t(91) = 4.08$, $p < .001$; reading comprehension, $t(91) = 2.89$, $p = .005$; and narrative scores, $t(91) = 3.53$, $p = .001$. Figure 7 shows mean speech recognition for children with NH, separated according to the SNR at which sentences were presented,

Figure 6. Mean percent correct for word reading, reading comprehension, and narrative scores for children with normal hearing (NH) and children with cochlear implants (CI) at fourth grade.

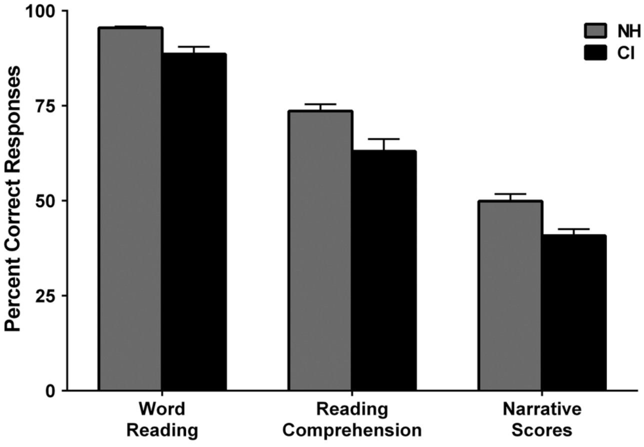
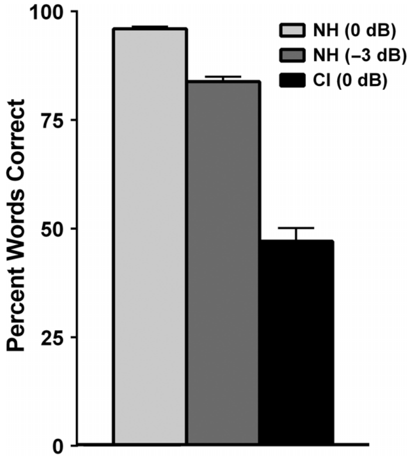


Figure 7. Mean percent correct word recognition for speech in noise, depending on signal-to-noise ratio (0 dB or −3 dB) and group (normal hearing [NH] or cochlear implant [CI]).



and for children with CIs. Scores for all three groups differed from each other: children with NH, depending on SNR, $t(44) = 9.90$, $p < .001$; children who heard the sentences at 0 dB, depending on group, $t(68) = 13.26$, $p < .001$; and children with NH who heard the sentences at −3 dB versus children with CIs who heard the sentences at 0 dB, $t(66) = 8.27$, $p < .001$.

Next, a series of separate regression analyses were conducted to determine the relationships among the predictor variables of interest and the dependent measures examined here. For predictor variables, both recall accuracy and response time were used, along with phonological awareness, expressive vocabulary, and nonverbal IQ. The dependent measures were word reading, reading comprehension, narrative abilities, and speech recognition. Table 3 shows standardized (β) coefficients for each predictor variable for each dependent measure. Response time is not shown on this table, because it was not found to be significantly related to any of the dependent measures for either group. Speech recognition is not shown on this table, because only one predictor was found to be significant, phonological awareness, and only for children with CIs, $\beta = .439$, $p < .01$.

Looking at the other dependent measures, it can be seen that more predictor variables were significantly related to the dependent measures for children with CIs than for children with NH. It can also be seen that nonverbal IQ explained a significant amount of variability in only one measure, word reading, for only one group, children with CIs. Of most interest to the current report is the finding that recall accuracy, which corresponds to what is typically measured in tasks of verbal working memory, predicted a significant amount of variability for children with NH on word reading only and for children with CIs on all three dependent measures. That outcome matches outcomes of other studies, showing that working memory was significantly related to other language skills. However, when stepwise regression analyses were conducted, a different pattern emerged. For word reading by children with NH, once variability explained by phonological awareness was accounted for, recall accuracy explained no additional variability. For children with CIs, phonological awareness, $\beta = .483$, $p < .001$, and vocabulary, $\beta = .377$, $p = .002$, were part of the resulting model explaining word reading, but not recall accuracy or nonverbal IQ. For reading comprehension by children with CIs, recall accuracy, $\beta = .472$, $p < .001$, and vocabulary, $\beta = .412$, $p = .001$, explained significant amounts of variability; phonological awareness explained no additional variability. For narrative abilities, only the vocabulary measure emerged in the stepwise regression as explaining a significant amount of variability for children with CIs. Thus, although recall accuracy was a significant predictor for these three dependent measures when used in separate, bivariate regressions, when other, related predictors were considered, it accounted for a significant amount of unique variability in only one of them, reading comprehension, for children with CIs. In fact, vocabulary was the most consistent predictor for these other language and literacy measures.

Table 3. Standardized coefficients for each of four predictor variables for each of three dependent measures, computed separately for children with normal hearing (NH) and children with cochlear implants (CI).

	Predictor variables			
Dependent measures	**Recall accuracy**	**Phonological awareness**	**Vocabulary**	**Nonverbal IQ**
Word reading				
NH	**.409****	**.515****	.075	.080
CI	**.540****	**.647****	**.588****	**.339***
Reading comprehension				
NH	−.028	−.012	**.474****	.004
CI	**.725****	**.477****	**.702****	.267
Narrative abilities				
NH	.249	.122	.242	.011
CI	**.421****	**.403****	**.457****	.257

Note. Significant coefficients are in bold.

$^{*}p < .05$. $^{**}p < .01$.

Discussion

This third part of the report was undertaken to assess which language and literacy measures are affected by verbal working memory for children with NH and for children with CIs. In general, it was found that a broader array of predictor variables explained outcomes on the set of dependent measures evaluated in this section for children with CIs than for children with NH. However, verbal working memory was found to explain a significant amount of unique variance only for reading comprehension and only for children with CIs. Overall, vocabulary abilities seemed to be the most important predictor variable in these analyses, accounting for outcomes on three of the four measures. Next was phonological awareness, which accounted for outcomes on two of the measures.

General Discussion

This report was undertaken to examine verbal working memory in children with hearing loss, in this case, specifically with CIs. This phenomenon has previously been assessed in this population, and verbal working memory has consistently been found to be deficient in children with hearing loss who receive CIs. It has also been found to account for some of the observed deficits in language and literacy skills of children with CIs. Nonetheless, uncertainty has surrounded these findings, both because potential sources of the verbal working memory deficit have not been thoroughly explored and because other potential predictors of language and literacy skills were not included in analyses when verbal working memory was found to explain outcomes for other language functions. This report especially examined whether evidence could be found to support each of two accounts offered previously to explain the verbal working memory deficits of children with CIs: the auditory scaffolding hypothesis and the phonological bottleneck hypothesis.

Verbal Working Memory Skills

The first part of this report examined differences in verbal working memory for children with CIs, compared to children with NH. Both recall accuracy and response times were investigated. The former was used as an index of how well the verbal material was encoded and stored in the short-term memory buffer; the latter was used as an index of how well children could process the stored items. Although both components of verbal working memory were found to operate more poorly for children with CIs than for children with NH, effect size was greater for recall accuracy than for response time: .96 versus .65. When these outcomes at fourth grade are compared to those from second grade for the same children, the magnitude of the deficit in storage appears to be roughly the same. In fact, recall accuracy of children with CIs at fourth grade matched fairly closely the accuracy of children with NH at second grade, indicating that children with CIs are roughly 2 years delayed in development of verbal working memory capacities. Where response time is concerned, children with NH improved slightly more than children with CIs. This likely reflects enhancements in processing efficiency acquired by children with NH, but not by those with CIs. This finding is of little consequence, however, because response times did not help to explain group differences in serial recall accuracy.

The potential effects of relevant treatment factors on verbal working memory were examined for these children with CIs, as well. The duration of auditory deprivation—meaning the period before identification or implantation—was not found to explain any variability in outcomes among children with CIs. That finding may provide evidence that contradicts the auditory scaffolding hypothesis, but it may be that all children with CIs had similarly poor sequential processing abilities. There was a trend for children who had a period of bimodal stimulation to perform slightly better than children who did not have any such period of stimulation. It is tempting to attribute this outcome to the possibility that children for whom the decision was made to provide bimodal stimulation may have had more residual hearing than children who were not provided with bimodal stimulation, but preimplant auditory thresholds did not explain any variability in working memory for these children.

Potential Sources of Variability

A second goal of this study was to examine the language and cognitive functions that account for variability in verbal working memory for children with NH and for those with CIs. Three potential sources of variability were examined: phonological awareness, vocabulary abilities, and nonverbal IQ. Different relationships were observed between predictor variables and the dependent measure of recall accuracy for the two groups. For children with NH, phonological awareness was the only factor that explained any variability in outcomes. This finding matches those of previous studies and fits with the notion that a phonological loop is instrumental for extracting phonological structure from the speech signal and using it to encode words into the memory buffer. For children with CIs, vocabulary was found to account for the most variability in verbal working memory outcomes. However, this finding must be interpreted with caution. In this instance, it does not suggest that having a larger vocabulary itself is responsible for the effect. Rather, this finding was related to the notion of lexical restructuring. This commonly accepted model of language acquisition proposes that the lexicon originally consists of unanalyzed forms, meaning whole words or brief, formulaic phrases such as “all gone.” This structure contrasts with the mature lexicon, which is thought to be composed of items with well-defined phonological structure (Luce & Pisoni, 1998). These descriptions refer to linguistic units but can be related to different levels of acoustic structure. In particular, children’s earliest word units are believed to be represented by coarse acoustic structure, meaning relatively gradual changes in broad spectral shape across time. As children mature, they simultaneously restructure their lexicons to consist of phonological representations and learn to attend to spectrotemporal details in the acoustic signal. Although these processes can be described separately, they are probably related: Access to spectrotemporal detail in the acoustic signal is needed in order to acquire sensitivity to phonological structure, and an expanding lexicon helps to drive the child's discovery of the spectrotemporal detail needed for phonological representations (Nittrouer, 2006). Children with CIs likely encounter challenges with lexical restructuring, because the degraded signals they receive through their devices make it difficult to acquire sensitivity to phonological structure. Where verbal working memory is concerned, this means they are restricted to using a coarser kind of structure for coding items into a memory buffer. This coarser structure is apparently less efficient for storage. Nonetheless, to the extent that the degree of signal degradation imposed by CIs and the conditions of the auditory system vary across children with CIs, signal clarity explains storage integrity in both short-term and long-term memory. This account supports the phonological bottleneck hypothesis as explanation for the verbal working memory deficits found for children with CIs.

Potential Dependent Functions

The third part of this study was concerned with investigating the language, literacy, and speech recognition skills that have been found to depend on verbal working memory abilities in children with CIs. These included word reading, reading comprehension, narrative abilities, and speech recognition in noise. Although different instruments have been used to measure these abilities, they are typically the ones thought to depend on verbal working memory (Bharadwaj et al., 2015; Daza et al., 2014; Edwards et al., 2016; Fagan et al., 2007; Kronenberger et al., 2014). However, in those earlier studies, verbal working memory was examined as a potential predictor of language, literacy, or speech recognition skills, independent of the factors found to underlie it, such as vocabulary. In fact, in Kronenberger et al. (2014), vocabulary was included as one measure in the construction of a latent language variable. Thus, it is not surprising that a significant relationship was found between the latent language measure and verbal working memory. However, this could reflect the idea that variability in both vocabulary development and verbal working memory are related to a common underlying factor for children with CIs, which is how clear the signal is.

In the current study, a principal metric of verbal working memory—recall accuracy—was found to explain a significant amount of unique variance in only one dependent language function for children with CIs: reading comprehension. Otherwise, the size of children's vocabularies explained the most variability in all of the measures examined as potentially dependent upon verbal working memory. However, it is suggested that vocabulary size itself is not the chief determinant of these skills but rather is a proxy for the extent of signal degradation experienced. Children with CIs uniformly have poor sensitivity to phonological structure due to the degraded nature of the signals they receive. As a consequence, they must perform language and related cognitive functions using coarser kinds of linguistic structures. To the extent that they are able to represent verbal material with a more refined representation, they are able to handle language functions more effectively. But this restriction on linguistic structure imposes fundamental limitations on many language and cognitive processes, demonstrating that the nature of sensory input has strong effects on the development of these processes.

The failure to find strong relationships between verbal working memory and other language functions, including speech recognition in noise, when other investigators (e.g., Kronenberger et al., 2014; Rudner et al., 2012) have done so could reflect differences in participants or in procedures across studies. For example, Kronenberger et al. (2014) tested individuals with hearing loss across the broad range of ages of 7–27 years, ensuring a great deal of variability on all scores. In the current study, age range was highly constrained. And in most studies evaluating verbal working memory as a potential contributor to the ease of language understanding, which includes the Rudner et al. (2012) study, working memory has been evaluated using reading or listening span tasks. Linguistic and cognitive factors can influence performance on these span tasks, so it is possible that these factors actually accounted for observed relationships between working memory span and speech recognition measures.

Summary

This study examined verbal working memory in children with CIs. There were three primary goals addressed by this work: (a) examining the extent and nature of the deficit exhibited by children with CIs; (b) exploring the sources of this deficit, including treatment variables and other language factors; and (c) examining the language and literacy functions that seemed likely at the outset of this study to be affected by deficits in verbal working memory. Results demonstrated that children with CIs were roughly 2 years delayed in the development of verbal working memory capacities. Both the storage and processing components of verbal working memory were affected, and those effects were largely independent of each other. The sources of variability for the two groups of children differed, with phonological awareness explaining most of the variability in storage for children with NH and vocabulary explaining the most variability for children with CIs. But a caveat is associated with the last finding, which is that the relationship may most appropriately indicate that the robustness of the signal can explain both vocabulary size and verbal working memory capacity for children with CIs, that is, short-term and long-term storage of words. Functions that have previously been found to be dependent on verbal working memory were examined in conjunction with other, related skills. It was found that phonological awareness was the primary source of variability in presumed dependent functions for children with NH, whereas vocabulary was the primary source of variability for children with CIs. Overall, the working memory and language functions of children with CIs appeared constrained by their poor sensitivity to phonological structure, arising from the degraded signals to which they have access. Instead, they must rely on coarser levels of linguistic structure for these functions.

Limitations of the Current Study

Although the conclusions that emerge from these data are clear, a couple limitations of this study could be cited. First, the groups of children were homogeneous. In particular, the children with CIs generally received those CIs very early, before the age of 3 years. For the most part, the few children who received CIs later than that had more residual hearing, likely protecting them from the commonly cited deleterious effects of late implantation. Stronger relationships between the age of first CI and the dependent measures may have been found if children with profound losses who received their CIs later had been included. In addition, only one measure of verbal working memory was used. Although adequate validity and reliability may be attributed to this measure, different outcomes may have been found if a reading or listening span task had been used.

Potential Clinical Implications

The main outcome of this report is that the quality of the signal available through CIs continues to constrain language and cognitive development for the children who wear them. This outcome was found for these children, even though they all wore fairly recent generations of implants and processors. Presumably, as newer devices that address the challenges of providing adequate spectral resolution become available, the problems observed for these children will dissipate. In the meantime, educators and clinicians are left to address the disproportionately large phonological deficit facing children who must acquire language through CIs. One consequence of this deficit is a problem in storage for working memory. Although more work is needed to reveal the best ways to ameliorate the problems caused by poor working memory in these children, reasonable measures should be taken in academic settings to facilitate their learning in spite of these problems. Such measures would include honing phonological skills as much as possible within the constraints of poor signal quality, keeping sets of oral instructions short, and providing visual aids whenever possible.

Acknowledgments

This work was supported by National Institute on Deafness and Other Communication Disorders Grant R01 DC006237 to Susan Nittrouer.

References

Ambrose, S. E., Fey, M. E., & Eisenberg, L. S. (2012). Phonological awareness and print knowledge of preschool children with cochlear implants. *Journal of Speech, Language, and Hearing Research, 55,* 811–823.

Arehart, K. H., Souza, P., Baca, R., & Kates, J. M. (2013). Working memory, age, and hearing loss: Susceptibility to hearing aid distortion. *Ear and Hearing, 34,* 251–260.

Baddeley, A. D. (1992). Working memory. *Science, 255,* 556–559.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417–423.

Baddeley, A. D. (2007). *Working memory, thought and action*. Oxford, United Kingdom: Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (pp. 47–89). New York, NY: Academic Press.

Baddeley, A., Lewis, V. J., & Vallar, G. (1984). Exploring the articulatory loop. *The Quarterly Journal of Experimental Psychology, 36,* 233–252.

Bar-Shalom, E. G., Crain, S., & Shankweiler, D. (1993). A comparison of comprehension and production abilities of good and poor readers. *Applied Psycholinguistics, 14,* 197–227.

Bharadwaj, S. V., Maricle, D., Green, L., & Allman, T. (2015). Working memory, short-term memory and reading proficiency in school-age children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology, 79,* 1647–1653.

Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology, 35,* 345–367.

Brownell, R. (2000). *Expressive One-Word Picture Vocabulary Test–Third Edition (EOWPVT-3)*. Novato, CA: Academic Therapy Publications.

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review, 106,* 551–581.

Burkholder, R. A., & Pisoni, D. B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology, 85,* 63–88.

Campbell, R., & Dodd, B. (1980). Hearing by eye. *Quarterly Journal of Experiemental Psychology, 32,* 85–99.

Campbell, R., Dodd, B., & Brasher, J. (1983). The sources of visual recency: Movement and language in serial recall. *Quarterly Journal of Experimental Psychology Section A-Human Experimental Psychology, 35*(Pt 4), 571–587.

Conway, C. M., & Christiansen, M. H. (2005). Modality-constrained statistical learning of tactile, visual, and auditory sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 24–39.

Conway, C. M., Pisoni, D. B., & Kronenberger, W. G. (2009). The importance of sound for cognitive sequencing abilities: The auditory scaffolding hypothesis. *Current Directions in Psychological Science, 18,* 275–279.

Crain, S. (1989). Why poor readers misunderstand spoken sentences. In D. Shankweiler & I. Y. Liberman (Eds.), *Phonology and reading disability: Solving the reading puzzle* (pp. 133–165). Ann Arbor, MI: The University of Michigan Press.

Crain, S., Shankweiler, D., Macaruso, P., & Bar-Shalom, E. G. (1990). Working memory and sentence comprehension: Investigations of children with reading disorder. In G. Vallar & T. Shallice (Eds.), *Neuropsychological impairments of short-term memory* (pp. 477–508). Cambridge, United Kingdom: Cambridge University Press.

Daza, M. T., Phillips-Silver, J., Ruiz-Cuadra, M. M., & López-López, F. (2014). Language skills and nonverbal cognitive processes associated with reading comprehension in deaf children. *Research in Developmental Disabilities, 35,* 3526–3533.

Edwards, L., Aitkenhead, L., & Langdon, D. (2016). The contribution of short-term memory capacity to reading ability in adolescents with cochlear implants. *International Journal of Pediatric Otorhinolaryngology, 90,* 37–42.

Fagan, M. K., Pisoni, D. B., Horn, D. L., & Dillon, C. M. (2007). Neuropsychological correlates of vocabulary, reading, and working memory in deaf children with cochlear implants. *Journal of Deaf Studies & Deaf Education, 12,* 461–471.

Fey, M. E., Catts, H. W., Proctor-Williams, K., Tomblin, J. B., & Zhang, X. (2004). Oral and written story composition skills of children with language impairment. *Journal of Speech, Language, and Hearing Research, 47,* 1301–1318.

Füllgrabe, C., & Rosen, S. (2016). Investigating the role of working memory in speech-in-noise identification for listeners with normal hearing. *Advances in Experimental Medicine and Biology, 894,* 29–36.

Hall, J. W., Wilson, K. P., Humphreys, M. S., Tinzmann, M. B., & Bowyer, P. M. (1983). Phonemic-similarity effects in good vs. poor readers. *Memory & Cognition, 11,* 520–527.

Harrison Bush, A. L., Lister, J. J., Lin, F. R., Betz, J., & Edwards, J. D. (2015). Peripheral hearing and cognition: Evidence from the Staying Keen in Later Life (SKILL) study. *Ear and Hearing, 36,* 395–407.

Hirsh, I. J., Reynolds, E. G., & Joseph, M. (1954). Intelligibility of different speech materials. *The Journal of the Acoustical Society of America, 26,* 530–538.

Hirshorn, E. A., Dye, M. W., Hauser, P., Supalla, T. R., & Bavelier, D. (2015). The contribution of phonological knowledge, memory, and language background to reading comprehension in deaf populations. *Frontiers in Psychology, 6,* 1153.

James, D., Rajput, K., Brown, T., Sirimanna, T., Brinton, J., & Goswami, U. (2005). Phonological awareness in deaf children who use cochlear implants. *Journal of Speech, Language, and Hearing Research, 48,* 1511–1528.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122–149.

Katz, R. B., Shankweiler, D., & Liberman, I. Y. (1981). Memory for item order and phonetic recording in the beginning reader. *Journal of Experimental Child Psychology, 32,* 474–484.

Kronenberger, W. G., Colson, B. G., Henning, S. C., & Pisoni, D. B. (2014). Executive functioning and speech-language skills following long-term use of cochlear implants. *Journal of Deaf Studies & Deaf Education, 19,* 456–470.

Leslie, L., & Caldwell, J. (2006). *Qualitative Reading Inventory–Fourth Edition*. New York, NY: Pearson.

Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19,* 1–36.

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *International Journal of Audiology, 42*(Suppl. 1), S49–S58.

Mann, V. A., & Liberman, I. Y. (1984). Phonological awareness and verbal short-term memory. *Journal of Learning Disabilities, 17,* 592–599.

Miller, G. A., Heise, G. A., & Lichten, W. (1951). The intelligibility of speech as a function of the context of the test materials. *Journal of Experimental Psychology, 41,* 329–335.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America, 95,* 1085–1099.

Nittrouer, S. (2006). Children hear the forest. *The Journal of the Acoustical Society of America, 120,* 1799–1802.

Nittrouer, S. (2010). *Early development of children with hearing loss*. San Diego, CA: Plural Publishing.

Nittrouer, S., & Burton, L. T. (2005). The role of early language experience in the development of speech perception and phonological processing abilities: Evidence from 5-year-olds with histories of otitis media with effusion and low socioeconomic status. *Journal of Communication Disorders, 38,* 29–63.

Nittrouer, S., Caldwell, A., & Holloman, C. (2012). Measuring what matters: Effectively predicting language and literacy in children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology, 76,* 1148–1158.

Nittrouer, S., Caldwell-Tarr, A., & Lowenstein, J. H. (2013). Working memory in children with cochlear implants: Problems are in storage, not processing. *International Journal of Pediatric Otorhinolaryngology, 77,* 1886–1898.

Nittrouer, S., Caldwell-Tarr, A., Moberly, A. C., & Lowenstein, J. H. (2014). Perceptual weighting strategies of children with cochlear implants and normal hearing. *Journal of Communication Disorders, 52,* 111–133.

Nittrouer, S., & Lowenstein, J. H. (2015). Weighting of acoustic cues to a manner distinction by children with and without hearing loss. *Journal of Speech, Language, and Hearing Research, 58,* 1077–1092.

Nittrouer, S., Lowenstein, J. H., & Holloman, C. (2016). Early predictors of phonological and morphosyntactic skills in second graders with cochlear implants. *Research in Developmental Disablities, 55,* 143–160.

Nittrouer, S., Lowenstein, J. H., Wucinich, T., & Moberly, A. C. (2016). Verbal working memory in older adults: The roles of phonological capacities and processing speed. *Journal of Speech, Language, and Hearing Research, 59,* 1520–1532.

Nittrouer, S., & Miller, M. E. (1999). The development of phonemic coding strategies for serial recall. *Applied Psycholinguistics, 20,* 563–588.

Nittrouer, S., Sansom, E., Low, K., Rice, C., & Caldwell-Tarr, A. (2014). Language structures used by kindergartners with cochlear implants: Relationship to phonological awareness, lexical knowledge and hearing loss. *Ear and Hearing, 35,* 506–518.

Nunnally, J. C., & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). New York, NY: McGraw-Hill.

Pisoni, D. B., & Cleary, M. (2004). Learning, memory and cognitive processes in deaf children following cochlear implantation. In F. G. Zeng, A. N. Popper, & R. R. Fay (Eds.), *Cochlear implants: Auditory prostheses and electric hearing* (pp. 377–426). Springer handbook of auditory research. New York, NY: Springer-Verlag.

Pisoni, D. B., Kronenberger, W. G., Chandramouli, S. H., & Conway, C. M. (2016). Learning and memory processes following cochlear implantation: The missing piece of the puzzle. *Frontiers in Psychology, 7,* 493.

Pollack, I., Rubenstein, H., & Decker, L. (1959). Intelligibility of known and unknown message sets. *The Journal of the Acoustical Society of America, 31,* 273–279.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126,* 841–865.

Reinhart, P. N., & Souza, P. E. (2016). Intelligibility and clarity of reverberant speech: Effects of wide dynamic range compression release time and working memory. *Journal of Speech, Language, and Hearing Research, 59,* 1543–1554.

Ritchie, S. J., Bates, T. C., & Plomin, R. (2015). Does learning to read improve intelligence? A longitudinal multivariate analysis in identical twins from age 7 to 16. *Child Development, 86,* 23–26.

Roid, G. H., & Miller, L. J. (2002). *Leiter International Performance Scale–Revised (LIPS-R)*. Wood Dale, IL: Stoelting.

Rönnberg, J. (2003). Cognition in the hearing impaired and deaf as a bridge between signal and dialogue: A framework and a model. *International Journal of Audiology, 42*(Suppl 1), S68–S76.

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., . . . Rudner, M. (2013). The ease of language understanding (ELU) model: Theoretical, empirical, and clinical advances. *Frontiers in Systems Neuroscience, 7,* 31.

Rudner, M., Lunner, T., Behrens, T., Thorén, E. S., & Rönnberg, J. (2012). Working memory capacity may influence perceived effort during aided speech recognition in noise. *Journal of the American Academy of Audiology, 23,* 577–589.

Shand, M. A., & Klima, E. S. (1981). Nonauditory suffix effects in congenitally deaf signers of American Sign Language. *Journal of Experimental Psychology-Human Learning and Memory, 7,* 464–474.

Shankweiler, D., Liberman, I. Y., Mark, L. S., Fowler, C. A., & Fischer, F. W. (1979). The speech code and learning to read. *Journal of Experimental Psychology-Human Learning and Memory, 5,* 531–545.

Snowling, M. J. (2000). *Dyslexia*. Oxford, United Kingdom: Blackwell.

Souza, P., & Arehart, K. (2015). Robust relationship between reading span and speech recognition in noise. *International Journal of Audiology, 54,* 705–713.

Spencer, L. J., & Tomblin, J. B. (2009). Evaluating phonological processing skills in children with prelingual deafness who use cochlear implants. *Journal of Deaf Studies and Deaf Education, 14,* 1–21.

Sperlich, A., Meixner, J., & Laubrock, J. (2016). Development of the perceptual span in reading: A longitudinal study. *Journal of Experimental Child Psychology, 146,* 181–201.

Spoehr, K. T., & Corin, W. J. (1978). The stimulus suffix effect as a memory coding phenomenon. *Memory & Cognition, 6,* 583–589.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry and Allied Disciplines, 45,* 2–40.

Walley, A. C., Metsala, J. L., & Garlock, V. M. (2003). Spoken vocabulary growth: Its role in the development of phoneme awareness and early reading ability. *Reading and Writing: An Interdisciplinary Journal, 16,* 5–20.

Walley, A. C., Smith, L. B., & Jusczyk, P. W. (1986). The role of phonemes and syllables in the perceived similarity of speech sounds for children. *Memory & Cognition, 14,* 220–229.

Woynaroski, T., Yoder, P., & Watson, L. R. (2016). Atypical cross-modal profiles and longitudinal associations between vocabulary scores in initially minimally verbal children with ASD. *Autism Research, 9,* 301–310.

Appendix (p. 1 of 4)

Scoring Categories and Criteria for the Elicited Narrative

1. Introduction/setting	
0 points = unsatisfactory	- No introduction is given - Narrative begins with an action
1 point = needs improvement	Child answers only one of the following questions: When? Who? Where?
2 points = satisfactory	Child answers only two of the following questions: When? Who? Where?
3 points = excellent	Child answers all three of the following questions: When? Who? Where?

2. Plot	
0 points = unsatisfactory	No goal, problem, or resolution
1 point = needs improvement	Child provides only one of the following: Goal, Problem, Resolution
2 points = satisfactory	Child provides only two of the following: Goal, Problem, Resolution
3 points = excellent	Child provides all three of the following: Goal, Problem, Resolution

3. Character descriptions/development	
0 points = unsatisfactory	Child fails to describe any characters/entities, or if he/she does, character labels are of the most basic level (e.g., *the boy, the girl, the bat*)
1 point = needs improvement	- Limited description of one character/entity (e.g., *sister, friend, the gray bat;* names) - Or the same description is attributed to more than one character/entity
2 points = satisfactory	- In-depth description of one character/entity - Or limited descriptions of several characters/entities
3 points = excellent	- In-depth descriptions of more than one character/entity

Appendix (p. 2 of 4)

Scoring Categories and Criteria for the Elicited Narrative

4. Mental states (characters' thoughts and feelings)

0 points = unsatisfactory	No mental states
1 point = needs improvement	- One mental state given for one character/entity - Or the same mental state is attributed to more than one character/entity
2 points = satisfactory	- Several different mental states given for one character/entity - Or one mental state for several characters/entities (cannot use same mental state for all characters)
3 points = excellent	- Several mental states given for several characters/entities - One character inferring the mental state of another character - Sophisticated lexical items are used to describe mental states

5. Referencing

Does the listener know who and what the child is referring to at all times? Correct referencing involves using words such as personal pronouns (e.g., he, she, it, they), possessive pronouns (e.g., my, his, hers, your), and demonstratives (e.g., that, those, these) in place of previously introduced people, places, or things.

0 points = unsatisfactory	No correct referencing for any characters/entities, objects, or places
1 point = needs improvement	- Referencing attempts are made but significant error(s) occur - Child mentions characters/entities, objects, places that were never introduced or established
2 points = satisfactory	- Correct referencing is maintained, but the story is short and simple - Or the story is longer and more complex, but there are a few referencing errors
3 points = excellent	- All characters/entities, objects, and places are referenced correctly throughout a story that is longer and more complex - **Must have a plot score of 3 to get a 3 in this category**

6. Focus

A well-focused story has a beginning, middle, and end that tie together effortlessly to develop the plot. Well-focused stories do not stray from the plot.

0 points = unsatisfactory	- No clear focus - Sounds more like a series of random events instead of a story
1 point = needs improvement	- The majority of the story lacks focus - Very few c-units relate to the plot - Series of picture descriptions - Child is rambling
2 points = satisfactory	- Focus is maintained, but the story is short and simple - Or the story is longer and more complex, but the focus slips in a couple places
3 points = excellent	- Longer, more complex story that maintains focus - **Must have a plot score of 3 to get a 3 in this category**

Appendix (p. 3 of 4)

Scoring Categories and Criteria for the Elicited Narrative

7. Order

Do setting descriptions and events follow a logical progression?	
0 points = unsatisfactory	No logical progression
1 point = needs improvement	A few c-units are in logical order, but overall, setting descriptions and events occur in a random order
2 points = satisfactory	- All c-units follow a logical progression, but the story is short and simple - Or the story is longer, more complex, and generally follows a logical progression, but a few c-units seem out of order
3 points = excellent	- Longer, more complex story that follows a logical progression - **Must have a plot score of 3 to get a 3 in this category**

8. Details

This category assesses the child's use of elaborated phrases to describe events and provide extra information.	
0 points = unsatisfactory	Very short story with no supporting details
1 point = needs improvement	- Only a few details - The bare minimum: contains enough details for the reader to know the child is attempting to tell a story but no extra information is given
2 points = satisfactory	- Interesting, descriptive details are given, but the story is relatively short - Or the story is longer and more complex with adequate details, though additional elaborated descriptions and extra information would make the story more interesting and clearer for the reader
3 points = excellent	- Story is longer, more complex, and filled with explicit and interesting details, making the story both enjoyable and captivating

9. Narrative tense

Evaluation of narrative tense across c-units.	
0 points = unsatisfactory	Numerous tense errors make it impossible for the reader to determine whether the story events are occurring in the past or present
1 point = needs improvement	- Correct tense is maintained for most of the story but some errors exist - Form errors are common. For example, the child uses *was* instead of *were*; *dived* instead of *dove*
2 points = satisfactory	- Maintains correct tense, no form errors, but story is short and simple - Or the story is longer, is more complex, and maintains correct tense but may have a couple form errors
3 points = excellent	- Tense is used correctly (consistent throughout the story and no form errors), **and the narrative contains at least one change in tense that is appropriately implemented** (cannot be a character quote: e.g., *Sally said, "We need to go."*)

10. Vocabulary

0 points = unsatisfactory	- No use of descriptors - The same words are repeated throughout the narrative - Limited range of vocabulary
1 point = needs improvement	- A few descriptors might be used - Small range of vocabulary - Some words may be used too many times
2 points = satisfactory	- Contains a variety of descriptors - Doesn't use the same word repetitively
3 points = excellent	- Uses a variety of sophisticated descriptors - Language is colorful and entertaining - Impressive range of vocabulary

Appendix (p. 4 of 4)

Scoring Categories and Criteria for the Elicited Narrative

11. Ending

0 points = unsatisfactory	- No clear ending to the narrative - Reader is unsure of whether or not story has ended
1 point = needs improvement	- Abrupt, unexpected ending - No summarizing statement(s) - May end with a general statement (e.g., *the end*) before the story seems like it should be over
2 points = satisfactory	- Child provides summarizing statement(s), final reactions of the character(s), etc. - May have a general ending statement as well, but this is not necessary
3 points = excellent	- Child provides a moral

12. Cohesion

0 points = unsatisfactory	No use of cohesive conjunctions
1 point = needs improvement	- Cohesive conjunction attempts are made but significant error(s) exist - Story sounds choppy
2 points = satisfactory	- Cohesive conjunctions are used correctly and when appropriate, but the story is short and simple - Or the story is longer and more complex, but cohesive conjunctions are used incorrectly and/or not as often as they could be
3 points = excellent	- Story is longer and more complex, and cohesive conjunctions are used correctly and the narrative is easy to follow - **Must have a plot score of 3 to get a 3 in this category**