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Speed of Information Processing and Verbal Working Memory in Children and Adolescents with Cochlear Implants

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Abstract

Background: Verbal working memory delays are found in many deaf children with cochlear implants compared to normal-hearing peers, but the factors contributing to these delays are not well understood. This study investigated differences between cochlear implant users and normal-hearing peers in memory scanning speed during a challenging verbal working memory task. To better understand variability in verbal working memory capacity within each sample, associations between memory scanning speed, speech recognition, and language were also investigated.

Methods: 25 prelingually-deaf, early implanted children (age 8–17 years) with cochlear implants and 25 normal-hearing peers completed the WISC-V Letter-Number Sequencing (LNS) working memory task. Timing measures were made for response latency and average pause duration between letters/numbers recalled during the task. Participants also completed measures of speech recognition, vocabulary, and language comprehension.

Results: Children with cochlear implants had longer pause durations than normal hearing peers during 3-span LNS sequences, but the groups did not differ in response latencies or in pause durations during 2-span LNS sequences. In the sample of cochlear implant users, poorer speech recognition was correlated with longer pause durations during 2-span sequences, while poorer vocabulary and weaker language comprehension were correlated with longer response latencies during 2-span sequences. Response latencies and pause durations were unrelated to language in the normal-hearing sample.

Conclusion: Children with cochlear implants have slower verbal working memory scanning speed than children with normal hearing. More robust phonological-lexical representations of language in memory may facilitate faster memory scanning speed and better working memory in cochlear implant users.

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Keywords

deafness; cochlear implant; hearing; working memory; processing speed

Introduction

The efficacy of cochlear implants (CIs) is well-established for restoring components of hearing that support the development of spoken language skills[1–3]. Additionally, auditory experience and spoken language development in prelingually deaf, early implanted children with CIs also have downstream impacts on the development of some neurocognitive abilities, causing differences relative to normal-hearing (NH) peers and large within-group variability and individual differences within the population of CI users[4]. Explaining these delays and individual differences in neurocognitive functioning in children and adolescents with CIs is critically important for understanding outcomes and for guiding the development of interventions[5].

One of the most well-studied neurocognitive functioning domains in children with CIs is verbal working memory – the ability to hold linguistic information in short-term memory concurrent with other cognitive operations and demands[6, 7]. An extensive body of research has demonstrated that samples of children with CIs show verbal working memory delays relative to matched samples of NH peers[6–10]. Furthermore, significant variability and individual differences in verbal working memory skills are found within the population of CI users[5, 7]. Verbal working memory skills are associated with multiple domains of speech-language outcomes including vocabulary, comprehension, and speech recognition skills[8, 11], and experimental and longitudinal research indicates that verbal working memory underlies and supports robust spoken language functioning and development[12, 13]. Thus, verbal working memory is a foundational at-risk domain of neurocognitive functioning that impacts spoken language outcomes following implantation.

Despite the fundamental importance of verbal working memory outcomes for CI users, the reasons for the delays and individual differences in verbal working memory outcomes that are routinely found in the population of CI users are not well-understood. In NH populations, verbal working memory is highly dependent on the speed/rate of verbal rehearsal and scanning/retrieval of the contents of working memory[14–16]. Rehearsal speed allows for the refreshing of the contents of verbal working memory to prevent their decay, while scanning/retrieval speed allows for the contents of verbal working memory to be retrieved from immediate memory before interference or decay renders them inaccessible[14–18]. Thus, a potential explanation for verbal working memory delays in CI users may be slower speed/rate of rehearsal and scanning of working memory contents.

Prior work has demonstrated that children and adolescents with CIs have slower verbal rehearsal and memory scanning rates than NH peers and that these rates are associated with delays in verbal short term memory relative to NH peers and with variability in verbal short-term memory within the population of CI users[7, 19]. Burkholder and Pisoni[7, 19] studied memory scanning rates using the digit span forward task, which requires subjects to repeat, in forward order, a sequence of digits presented by the examiner. They measured rates of scanning/retrieval of items (digits) from short-term memory using pause durations between digits (defined as the time duration between the end point of a spoken digit in the subject's response until the start of the next spoken digit in the subject's response)[19, 20]. Prior work has demonstrated that interword pause durations during short-term memory tasks involving lists of words is a sensitive measure of the rate of memory search[21–23]. Burkholder and Pisoni[19] also measured response latencies (defined as the time from the end of the examiner's spoken stimulus until the beginning of the subject's spoken response), which reflect the preparatory time needed to process the stimulus and prepare the response[22]. Timing measurements were used only for correct responses (in order to ensure that reliable memory processing had occurred) and only for digit list spans of 4 or less for NH children (to ensure that equivalent span lengths were compared between NH and CI samples, because very few children in the CI sample had accurate spans greater than 4). Pause durations and latencies were averaged across all correct responses.

As expected, Burkholder and Pisoni[19] found shorter digit spans in children with CIs than in NH peers. Furthermore, children with CIs had pause durations between digits that were nearly three times as long as those of NH peers. No differences between groups were found in response latencies. Based on these findings and prior work on scanning speed[22], Burkholder and Pisoni concluded that children with CIs had slower verbal memory scanning speed than NH peers and that this slower scanning speed accounted for the shorter memory spans of children with CIs[20].

Although these findings provide important insights into the possible processes underlying verbal working memory delays in CI users, they are limited by the nature of the digit span forward task. Digit span forward requires short-term memory and recall of a list of digits in the same order in which they were presented, with no intervening or additional cognitive information processing demands. As a result, digit span forward has been characterized as a measure of short-term memory without concurrent processing and not as a measure of working memory requiring both short term memory and active, concurrent processing[24, 25]. It is not clear whether memory scanning speed differences between CI and NH samples would be found on a working memory task involving both short-term memory and concurrent processing demands. Because working memory tasks require this additional processing, response latency (which reflects processing that occurs prior to initiating the response) may be an additional important component of processing during a working memory task.

The present study sought to improve our understanding of verbal working memory delays and variability in children with CIs by addressing two research questions: (1) Do children with CIs show slower response latencies (reflecting processing prior to the response) and pause durations (reflecting memory scanning speed) than NH peers on a demanding test of verbal working memory? We used the Letter-Number Sequencing subtest of the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V)[26] because it is a well-accepted and validated test of verbal working memory that requires both short term memory (of a list of letters and digits) and concurrent, demanding mental processing (reordering the list to present digits first in ascending order, followed by letters in alphabetical order). Based on prior work with short-term memory tasks, we expected that CI users would show longer pause durations than NH peers, indicating slower memory scanning speed. Because prior work has been inconsistent about the degree to which processing delays contribute to verbal working memory differences between CI and NH samples[9, 10], we did not make an a priori hypothesis about differences in response latencies (as a measure of processing) between the samples. (2) Given the well-established association between verbal working memory capacity and speech-language outcomes in children with CIs, are verbal working memory response latencies and pause durations correlated with speech-language functioning in CI users? We expected that stronger speech-language skills would correlate with shorter pause durations because more robust phonological-lexical representations of words in memory (reflected by stronger speech-language skills) would support more efficient scanning and retrieval of words from verbal working memory.

Materials and Methods

Participants

Participants for the present study were 25 children and adolescents with CIs and 25 NH peers (Table 1). Inclusion criteria for the sample of CI users were: (1) hearing loss prior to age 3 years; (2) cochlear implantation at age 3 years, 11 months or younger; (3) enrolled or living in an environment that encourages the development and use of spoken language skills; and (4) use of CIs for at least 7 years. Inclusion criteria for the sample of NH peers were: (1) normal hearing and language by parent-report; and (2) hearing screening within normal range (each ear individually tested at frequencies of 500, 1000, 2000, and 4000 Hz at 20 dB HL using Telephonics TDH-50P headphones in an Acoustic Systems RE243 soundbooth). Inclusion criteria for both samples were: (1) age 8–17 years; (2) absence of developmental, cognitive, or neurological diagnoses; (3) home environment in which spoken English is the primary language; (4) nonverbal IQ greater than 2 SD below the normative mean.

Language inclusion criteria for the study were assessed using the parent-reported Language Experience Questionnaire (created in our lab for this project). Parents rate the child's amount of exposure to communication in spoken English, spoken Spanish, American Sign Language, Signed Exact English, Cued Speech, and other languages at home, school, and other settings on a 0 (not at all)-1 (less than once a week)-2 (at least once a week)-3 (every day, less than half of the time)-4 (every day, more than half of the time) scale. Participants were required to score "4" on spoken English used at home and school and 2 or less on ASL used at home in order to be entered into the study.

Procedures

Study procedures were approved by the local Institutional Review Board. Written consent and assent were obtained prior to initiation of study procedures. Tests were administered individually in a single session by ASHA-certified speech-language pathologists using standard instructions. Audiorecorded tests were presented in the soundbooth at 65 dB sound pressure level (SPL) using a high quality loudspeaker located approximately 3 feet from the participant.

Measures

Demographics, Audiological/Hearing History, and Nonverbal Intelligence— Demographic information was obtained by parent-report questionnaire and included age, gender, race/ethnicity, and family income (on a 1=under $20K/year to 8=$150K+/year scale). Audiological and hearing history variables obtained from the medical record and/or parent interview for the CI sample consisted of age of onset of deafness, duration of deafness, age of implantation, duration of CI use, unaided pre-implant pure tone average (PTA) in the best ear for frequencies 500, 1000, and 2000 Hz in dB HL, most recent aided PTA in the best ear, and parent-rated amount of CI use. Nonverbal intelligence was assessed using the Leiter-3 Classification and Analogies subtest[27], a picture-based measure of conceptual reasoning that yields norm-based scaled scores (normative mean=10, SD=3) (Table 1).

Letter-Number Sequencing—The Letter-Number Sequencing (LNS) subtest of the Wechsler Intelligence Scale for Children, Fifth Edition (WISC-V) presents a mixed sequence of letters and digits spoken live by the examiner (with face in view), which must be reordered and reproduced by the subject, with the digits first in ascending order, followed by the letters in alphabetical order (Figure 1). Stimulus sequences are presented in sets of three, starting with two sets of three sequences consisting of 1 digit and 1 letter (“Span 2;” e.g., F-7, 4-Y, R-2), followed by three sets of three sequences consisting of 2 digits and 1 letter or 1 digit and 2 letters (“Span 3;” e.g., 5-T-1, R-G-3, 6–3-M). Thereafter, sequence length increases by one with each set (e.g., 3 sequences at Span 4, and so on). The test is discontinued when the participant misses all three sequences in the same set. The LNS was administered in standard live-voice format, and subject responses were audiorecorded for later coding.

Two measures of response time were obtained from LNS responses, using established definitions and methods[19]. Response latency was defined as the time between the end of the examiner’s spoken stimulus sequence and the beginning of the subject’s first spoken item in the response. Pause duration was defined as the average time between the end of each digit or letter spoken by the subject and the beginning of the next digit/letter. Scores for response latency and pause duration were recorded only for correctly reproduced sequences. Average response latency and pause duration scores were calculated for each span length, because the difficulty of LNS sequences increases significantly with span length, resulting in significantly longer latencies and pause durations for longer span lengths. Thus, separate response latency and pause duration scores were obtained for Span 2, Span 3, and so on. Measurements were made using the Audacity application and were expressed in milliseconds (ms).

Speech Recognition—Speech recognition for single words and for words in sentences was assessed by the Lexical Neighborhood Test (LNT)[28] and the Hearing in Noise Test for Children (HINT-C)[29], respectively. The LNT is an open-set monosyllabic word recognition test. Participants repeated lexically easy (sharing few phonemes with other words in the lexicon) or lexically hard (more phonologically confusable) words presented via audio recording. In the present study, LNT Total Score was the percentage of total words correct.

For the HINT-C, participants repeated meaningful spoken sentences via audio recording in quiet and in speech-shaped noise (+5 dB signal-to-noise ratio). Scores for quiet and noise were derived from percentage of keywords correctly repeated by subjects. Because NH children routinely score at the ceiling on the LNT and HINT-C, these measures were administered only to CI users.

Language—Single-word receptive vocabulary knowledge was assessed using the Peabody Picture Vocabulary Test Fourth Edition (PPVT-4)[30]. On this test, participants choose one of four pictures matching a word spoken by the examiner. PPVT-4 age norm-based standard scores (normative mean=100, SD=15) were used to measure receptive vocabulary in this study. Comprehension of spoken directions was measured with the Following Directions subtest of the Clinical Evaluation of Language Fundamentals Fifth Edition (CELF-5)[31]. On this subtest, the examiner provides a set of spoken directions that the child follows by pointing to pictures. CELF-5 Following Directions age norm-based scaled scores (normative mean=10, SD=3) were used in this study to measure comprehension, memory, and sequential execution of spoken directions.

Results

Sample Characteristics, Nonverbal Intelligence, and Language

The CI and NH samples did not differ in age, gender, or household income level. However, the CI sample scored lower than the NH sample on the Leiter-3 Classification and Analogies subtest measure of nonverbal intelligence ($t(48)=2.25$, $p<0.05$)(Table 1). Additionally, the CI sample scored lower than the NH sample on the language measures of receptive vocabulary ($t(48)=5.21$, $p<0.001$) and following directions ($t(48)=4.60$, $p<0.001$)(Table 2).

Letter-Number Sequencing Comparisons between Hearing Groups

The CI and NH samples provided correct responses to almost all 2-Span LNS sequences (average proportion of 2-Span sequences answered correctly = 0.88 and 0.92, respectively; Table 2). For 3-Span LNS sequences, the NH group averaged a larger proportion correct than the CI group (0.92 vs. 0.73). However, for 4-Span LNS sequences, the CI sample averaged fewer than half of sequences correct (43%), and over half of subjects in the CI sample (52%; 13/25) answered 0 or only 1 of the 4-Span sequences correctly. As a result, response latencies and pause durations for correct sequences could not be reliably calculated for most CI users at the 4-Span (or greater) LNS sequence length. Results for response latencies and pause durations are therefore reported only for 2-Span and 3-Span LNS sequences.

All analyses were conducted on log-transformed data for pause durations or response latencies, consistent with recommendations for analysis of response time data[32–34]. The CI sample had significantly longer pause durations between recalled letters/digits for the 3-Span sequences than NH peers, but the samples did not differ in pause duration length for the 2-Span sequences (Table 2). CI and NH samples did not differ in response latencies for 2-Span or 3-Span LNS sequences.

Association of LNS Pause Durations and Response Latencies with Speech Recognition and Language Skills

CI users with poorer scores on the three measures of speech recognition (LNT, HINT-C in Quiet and Noise) had longer pause durations on 2-Span LNS sequences (Table 3). Pause durations for 3-Span LNS sequences, as well as response latencies for 2-Span and 3-Span sequences, were not significantly correlated with speech recognition scores in the CI sample. For language measures (PPVT-4 and CELF-5), higher scores were related to shorter response latencies in 2-Span sequences in the CI sample. Language scores were unrelated to pause durations or response latencies in the NH sample.

Discussion

This study sought to address two primary research questions in order to better understand factors contributing to verbal working memory delays and variability in children and adolescents with CIs: (1) Do children with CIs show slower response latencies (reflecting processing prior to the response) and pause durations (reflecting memory scanning speed) than NH peers on a demanding test of verbal working memory; and (2) Are verbal working memory response latencies and pause durations correlated with speech-language functioning in CI users? Unlike prior research, we used a challenging, well-validated task of verbal working memory (as opposed to short-term memory alone), and we investigated factors accounting for variability in verbal working memory timing scores. Study results demonstrated significantly longer pause durations in the CI sample than in the NH sample during 3-Span LNS sequences, but no differences were found between CI and NH samples in pause duration during 2-Span LNS sequences or in response latencies during 2- or 3-Span LNS sequences. Stronger speech recognition skills were associated with shorter pause durations for 2-Span (but not 3-Span) LNS sequences in the CI sample, while stronger language skills were associated with shorter response latencies for 2-Span (but not 3-Span) LNS sequences in the CI sample. Language skills were not associated with response latencies or pause durations in the NH sample.

CI users were less likely than NH peers to provide correct responses to 3-Span LNS sequences (73% vs. 92% respectively; Table 2), and their pause durations on those 3-Span sequences were over 50% longer than those of NH peers. In contrast, both groups showed strong performance on 2-Span LNS sequences (88% and 92% accurate, respectively) and did not differ in pause durations. These findings suggest that the poorer performance of CI users on the more demanding 3-Span task may have been due to slower memory scanning speed. The CI and NH samples did not differ on response latencies, suggesting that the speed of pre-response processing (concurrent memory during reordering of digits and letters) of the responses did not differ between groups. Thus, differences in memory scanning speed, not reordering speed, were found between the CI and NH samples. Notably, analyses with longer span sequences (e.g., 4-Span and longer) were not possible because of a low proportion of correct responses in the CI sample (43% of sequences correct, and over half of the CI sample answered one or fewer of the 4-Span sequences correctly). Unfortunately, the standard LNS administration presents only one set of 3 sequences for each span of 4 and greater, limiting the data available from correct responses at those spans; modified

LNS administrations presenting more sequences at the longer spans may allow for sufficient variability for analysis.

Despite differences between CI and NH samples in pause durations found on 3-Span LNS sequences, associations between pause durations, response latencies, and speech-language functioning were found only for 2-Span LNS sequences in the CI sample. The reasons for these discrepant findings for 3-Span and 2-Span sequences are not clear, warranting additional research. It is possible that the lack of significant associations between 3-Span LNS sequences and speech-language scores in the CI sample was a result of insufficient correct responses provided to 3-Span sequences in the CI sample (only 73% of sequences correct), which may have introduced too much error/variability in those timing scores. Administering additional 3-Span sequences may have produced more stable/consistent timing values.

For the 2-Span sequences in the CI sample, speech recognition correlated significantly with pause durations, whereas language correlated significantly with response latencies. Speech recognition may correspond more closely than language knowledge/processing to robust phonological representations of language in memory[7], which could support more efficient scanning and retrieval of verbal memory codes, resulting in faster pause durations. Language abilities, on the other hand, may reflect more higher-order processing efficiency for more complex cognitive operations such as reordering memory contents[3], which could facilitate shorter response latencies for response preparation/processing prior to recall. The absence of significant associations between language abilities and pause durations/response latencies in the NH group suggests that variability in language is more closely tied to verbal working memory processing in CI users than in NH peers, consistent with a large body of research demonstrating that verbal working memory and language skills are more closely connected in CI users than in NH peers[4, 6, 8, 12].

In summary, these results indicate that CI users show slower memory scanning speed than NH peers during a challenging verbal working memory task, providing support for one potential explanation for their poorer verbal working memory capacity. Stronger speech recognition skills were associated with faster memory scanning, consistent with hypotheses that more robust highly-detailed phonological-lexical representations of words in memory support faster scanning speed. Stronger language skills were associated with shorter response latencies, suggesting that language skills may support processing of memory contents in the form of active reordering during concurrent memory.

Clinically, these new findings suggest that strategies to improve scanning speed may enhance interventions for verbal working memory deficits in at-risk CI users[35]. Furthermore, the link between scanning speed and speech recognition suggests that strengthening phonological representations of words in memory and improving language knowledge and processing may have downstream positive effects on the efficiency of verbal working memory processing, potentially improving verbal working memory.

Limitations of the study include small sample sizes, which may have affected power for analyses with small-to-medium effect sizes. Additionally, results are correlational and cannot definitively show causality. Specifically, speech recognition and language skills may support verbal working memory, but it is also likely that verbal working memory supports speech recognition and language skills. Finally, because of limitations in number of correct responses in the CI sample, only 2-Span and 3-Span sequences could be analyzed for timing data.

Conflicts of Interest and Source of Funding:

William Kronenberger is a paid consultant to Takeda Pharmaceuticals and the Indiana Hemophilia and Thrombosis Center (none are relevant to the current article). No other authors have conflicts to declare. This work was supported by the National Institute on Deafness and Other Communication Disorders (R01DC015257 to WGK and DBP) and the Indiana Medical Student Program for Research and Scholarship (to RMH mentored by WGK for this work).

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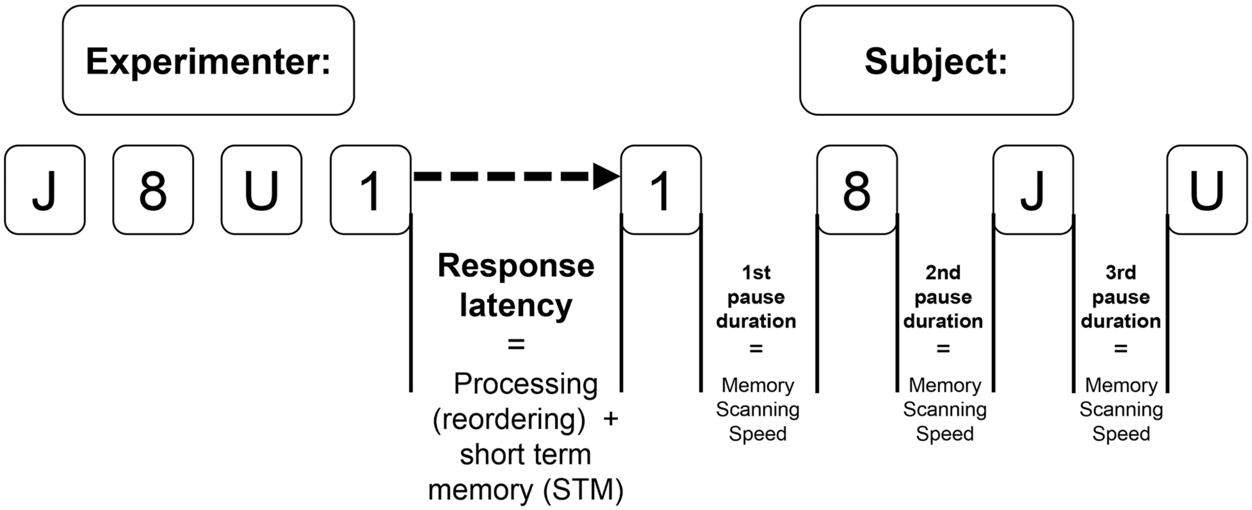

Figure 1.

Letter-Number Sequencing Task and Timing Values. Sample Letter-Number Sequencing item (Span 4) is depicted with stimulus sequence (read aloud by experimenter) and correct response (provided by subject) – digits first in ascending order, followed by letters in alphabetical order. Response latency is time between end of stimulus read by experimenter and first response of subject. Pause durations are time between end of letter/digit and start of next letter/digit spoken by subject.

Table 1

Sample Demographics and Hearing History

	Cochlear Implant (N=25)		Normal Hearing (N=25)		
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	***t***
Chronological Age[a]	12.1 (2.7)	8.7–17.3	11.8 (2.8)	8.2–17.6	0.34
Income Level[b]	4.7 (2.4)	1–8	4.1 (1.6)	2–8	1.11
Leiter-3 CA Subtest	11.1 (2.8)	7–17	12.9 (2.9)	7–19	2.25*
Age of Onset of Deafness[c]	1.8 (3.8)	0–12.0	NA	NA	NA
Duration of Deafness[c]	18.6 (8.8)	7.0–36.0	NA	NA	NA
Best Ear Preimplant PTA[d]	107.9 (9.0)	91.3–120.0	NA	NA	NA
Age at Implantation[c]	20.4 (9.0)	9.5–41.5	NA	NA	NA
Duration of CI Use[a]	10.4 (2.5)	7.3–16.2	NA	NA	NA
CI Usage Rating[e]	6.6 (0.7)	5–7	NA	NA	NA
Recent Aided PTA	20.5 (3.5)	13.8–30.0	NA	NA	NA
Home Spoken English Use[f]	4.0 (0.0)	4–4	4.0 (0.0)	4–4	NA
Home ASL Use[f]	0.1 (0.4)	0–2	0.1 (0.4)	0–2	NA
School Spoken English Use[f]	4.0 (0.0)	4–4	4.0 (0.0)	4–4	NA
School ASL Use[f]	0.3 (0.8)	0–3	0.0 (0.0)	0–0	NA
Gender (Female/Male) (N)	11/14		8/17		
Age of Onset of Deafness (N)					
Birth	19		NA		
1–6 Months	2				
6–12 months	4				
Race/Ethnicity					
Native American/Alaskan 1			0		
Asian	0		1		
Black or African-American 5			2		
White	23		24		
Hispanic/Latino	2		1		
Bilateral/Unilateral (N)					
Bilateral CIs	21		NA		
Unilateral CI	4				

Note: CI=cochlear implant; SD=standard deviation; NA=not applicable. Leiter-3 CA=Leiter-3 Classification and Analogies Subtest. Degrees of freedom (df) for t-tests=48; *p* value for gender obtained from a Fisher's exact test, 2-sided=0.56.

[a] in Years; ;

[b] On a 1 (under $20K/year) to 8 ($150K+/year) scale;

[c] in Months;

[d] PTA=pure-tone average for frequencies 500, 1000, 2000 Hz in dB HL;

[e] parent-rated use of CI (5=75% or more of the time [N=2]; 6=almost all of the time [N=7]; 7=all of the time [N=16]);

[f] from Language Experience Questionnaire ratings of 0 (not at all) through 4 (every day, more than half of the time).

* $p < .05$;

** $p < 0.01$;

*** $p < .001$

Table 2

Hearing Group Differences in Letter-Number Sequencing, Speech Recognition, and Language

	Cochlear Implant Mean (SD)	Normal Hearing Mean (SD)	t
Letter-Number Sequencing Proportion of Sequences Correct			
2-Span	0.88 (0.13)	0.92 (0.13)	1.09
3-Span	0.73 (0.29)	0.92 (0.12)	2.93**
4-Span	0.43 (0.38)	0.60 (0.33)	1.72[a]
Letter-Number Sequencing Pause Durations (milliseconds)			
2-Span	84.0 (80.8)	69.1 (75.9)	0.81
3-Span	284.9 (208.5)	186.5 (137.6)	2.17*
Letter-Number Sequencing Response Latencies (milliseconds)			
2-Span	966.5 (556.8)	888.2 (512.7)	0.37
3-Span	1962.7 (979.9)	2258.2 (1518.2)	0.51
Speech Recognition (% Keywords Correct)			
LNT - Total	84.8 (9.2)	-----	-----
HINT-C Quiet	92.4 (10.5)	-----	-----
HINT-C Noise	79.3 (21.4)	-----	-----
Language			
PPVT-4 (Standard Score)	89.5 (21.2)	118.4 (17.8)	5.21***
CELF-5 Following Directions (Scaled Score)	8.0 (3.5)	12.2 (2.4)	4.60***

Note: 2-Span, 3-Span, 4-Span=span length of Letter-Number Sequence in number of letters/digits (e.g., 2-Span=1 letter, 1 digit; 3-Span=1 letter, 2 digits or 2 letters, 1 digit, etc.). LNT=Lexical Neighborhood Test. HINT-C=Hearing in Noise Test for Children. PPVT-4=Peabody Picture Vocabulary Test, Fourth Edition. CELF-5=Clinical Evaluation of Language Fundamentals, Fifth Edition. Values for Lexical Neighborhood Test and HINT-C are % of keywords correct. df for t-tests=48. T-tests for pause durations and response latencies were conducted on log-transformed data.

[a] $p<0.10$;

* $p < .05$;

** $p < .01$;

*** $p < .001$ (2-tailed)

Table 3

Letter-Number Sequencing, Speech Recognition, and Language Correlations

	LNT	HINT-C Quiet	HINT-C Noise	PPVT-4	CELF-5 Following Directions
Letter-Number Sequencing Pause Durations					
2-Span					
CI	−0.43 *	−0.41 *	−0.43 *	−0.16	−0.35
NH	-----	-----	-----	−0.01	−0.31
3-Span					
CI	−0.21	−0.08	−0.35	0.14	−0.09
NH	-----	-----	-----	0.31	0.32
Letter-Number Sequencing Response Latencies					
2-Span					
CI	−0.33	−0.29	−0.21	−0.57 **	−0.53 **
NH	-----	-----	-----	−0.06	0.03
3-Span					
CI	−0.05	0.11	0.14	−0.12	−0.08
NH	-----	-----	-----	0.04	−0.03

Note: Values are Pearson correlations; top values are for cochlear implant sample; bottom values are for normal-hearing sample. CI=cochlear implant sample; NH=normal-hearing sample. LNT=Lexical Neighborhood Test. HINT-C=Hearing in Noise Test for Children. PPVT-4=Peabody Picture Vocabulary Test, Fourth Edition. CELF-5=Clinical Evaluation of Language Fundamentals, Fifth Edition. Analyses for pause durations and response latencies were conducted on log-transformed data.

* $p < .05$;

** $p < .01$ (2-tailed)