Published in final edited form as:
Otol Neurotol. 2013 April ; 34(3): 396–401. doi:10.1097/MAO.0b013e318277a0cb.

Complex Working Memory Span in Cochlear Implanted and Normal Hearing Teenagers

Ann E. Geers, Ph.D,
University of Texas at Dallas

David B. Pisoni, Ph.D, and
Indiana University

Christine Brenner, MS
Moog Center for Deaf Education

INTRODUCTION

The individual's capacity to maintain attention and process new information in the face of distraction is known in the literature as working memory (WM). Short term memory (STM) is used to encode and retain information for a short period of time. WM tasks are functionally distinct from STM tasks because they require not only information encoding, storage and rehearsal, but also include a processing/manipulation component requiring a dual task load, such as judging semantic acceptability of a sentence. STM tasks, such as word span or digit span, may be considered a subset of WM. STM requires simple storage, whereas WM requires a storage component as well as an active attention and control process. WM tasks have been found to differ from simple span tasks in their predictive validity, measuring variance that is unique from STM [1].

The current model of working memory developed by Baddeley and his colleagues consists of four components[2], (1) a domain-general central executive that controls attention and processing activities and regulates the flow of information in the processing system, (2) the phonological loop that is used for the temporary storage of verbal phonological memory codes, (3) the visual-spatial sketchpad that maintains and processes visual and spatial representations, and (4) the episodic buffer that is used to integrate and bind memory codes from different processing domains into larger chunks of information. The complex reading span task developed by Daneman & Carpenter [3] is among the most widely used tools for measuring the central executive function. The reading span task requires the participant to perform two operations at once: 1) read a series of sentences aloud and make a semantic acceptability judgment about the sentence and 2) keep track of the last word of each sentence so that the words can be recalled later. Reading span tasks have been found to have good reliability (i.e., .70 to .90) across a number of studies. Furthermore, performance on reading span tasks has been found to predict complex cognitive processes such as comprehension, problem solving and reasoning – all tasks that require "executive attention" [1].

Correspondence: Ann Geers, University of Texas at Dallas, Callier Center, 1966 Inwood Rd., Dallas, TX 75235. Telephone: 214-905-3116; FAX: 214-905-3146; ageers@utdallas.edu.

Reading span is thought to measure the capacity of the central executive because it requires simultaneous storage and processing of phonological and lexical information. Verbal storage uses a phonological loop, composed of a short-term phonological store subject to rapid decay plus a subvocal rehearsal process that can be used to refresh decaying representations within the store. Individuals with normal hearing perform similarly whether the task is presented through listening or through reading [3]. However, WM estimates might be expected to differ considerably for reading and listening tasks in populations with significant hearing loss.

Memory skills in Children with Hearing Loss

Memory studies of children with hearing loss have primarily used STM tasks. Stiles et al, [4] compared performance of 6-9 year olds with mild to moderate HL with NH age mates on both phonological and visuospatial STM tasks. Although articulation rate and vocabulary were lower in children with hearing loss than in age-mates with normal hearing, there was no significant effect of hearing loss on memory performance,. This stands in contrast to results for children with greater hearing losses who use CIs. Watson, et al, [5] found a marked impairment on digit span and non-word repetition measures for children with CIs compared to NH children. Similar results were reported by Pisoni[6] for digit span results obtained in CI users tested in both elementary grades and high school. When WM processes rely on verbal rehearsal and serial scanning of phonological information in STM, early severe-profound auditory deprivation seems to impair normal development. Reinstatement of auditory sensation in children with CIs was not sufficient to enable adequate development. Further evidence of this impairment is provided by examining the relationship between mismatch negativity activation and memory span. Connections between pre-attentive auditory sensory memory and “higher language functions” were apparent in NH children but not in age-matched CI users [5].

Objective of the Current Study

This investigation examined WM performance on a reading span task for a group of CI adolescents and compared these results with performance on STM (i.e. digit span) and verbal rehearsal speed (articulation rate) measures. It was hypothesized that CI adolescents would exhibit deficits in phonological processing compared to NH age-mates that would be reflected in STM tasks presented in an auditory modality. However, if WM were measured with a reading span task that required verbal processing in a visual modality, such deficits might not be observed. It was further hypothesized that STM and WM would contribute independently to language and reading outcomes in CI adolescents, reflecting a model that conceives of them as linked processes that have a cascading effect on verbal development.

Method

Participants

A follow-up study recruited 112 teenagers from a nationwide sample of 181 children who had used cochlear implants (CI) since preschool and were originally tested during the elementary grades. Follow-up participants ranged in age from 15.0 to 18.5 years (Mean = 16.7) and had used a CI for an average of 13.3 years. All participants were consistent CI users for more than 10 years with an average open set speech perception score on the Lexical Neighborhood Test [7] of 60%. The teenagers attended 3-day research “camps” in which they participated in an 8-hour test battery covering a range of speech perception, speech production, language, cognitive, academic and social skills[8]. Performance IQ scores on the Wechsler Intelligence Scale for Children (WISC)[9] averaged 103.1, which did not differ significantly from the normative sample of hearing age-mates (i.e., PIQ = 100; SD = 15). A control group of 46 teenagers with normal hearing (NH) from public high schools in the St. Louis metropolitan area participated in a shortened test battery primarily consisting of those measures that did not have age-appropriate normative data. All NH students passed a hearing screening at 15 dB HL from 250 to 8000 Hz in both ears.

Sample characteristics of the CI and NH samples are compared in Table 1 along with their scores on selected tests administered to both groups. The majority of participants in both groups came from families in which at least one parent had completed college, indicating relatively "privileged" socio-economic environments. While average vocabulary and reading scores were within one standard deviation of the normative sample mean for both groups, the NH participants exhibited higher receptive vocabulary scores on the Peabody Picture Vocabulary Test [10] and higher general vocabulary and paragraph reading scores on the Test of Reading Comprehension (TORC) [11] than the CI participants. Since scores on the PPVT were highly correlated with scores on the entire language test battery[12] and TORC scores were representative of results on the entire literacy battery[13], these two scores are used here to represent overall language and overall literacy skills, respectively.

All participants signed an assent form, and their parents signed a consent form approved by the Institutional Review Board of the University of Texas at Dallas. A complete description of participants is provided in a published article [14].

Methods and Materials

Digit Span

Digit Span Forward (DSF) and Digit Span Backward (DSB) measures were obtained from the CI group using the Digit Span Subtest of the WISC-III [9]. All subjects were tested by the same examiner. The subject repeated lists of digits spoken live-voice at a rate of one digit per second. Administration was conducted with both auditory and visual cues at a close range. Forward span required simply repeating back the series of digits, while backward span required repeating the digits in reverse order.

Two lists were presented at each list length, beginning with a length of two digits and increasing in length by one digit after each successful repetition of at least one list at a given length. Testing of DSF or DSB was discontinued when a child repeated two lists incorrectly at the same length. "Longest Span Score" was the longest series repeated in the DSF and DSB conditions. The total number of lists correctly repeated in both conditions was converted to a scaled score based on age-appropriate norms from the WISC-III test manual[9].

Reading Span

WM was measured in both CI and NH subjects with a "reading span" task that was adapted from Daneman and Carpenter[3]. Subjects were asked to read aloud sentences printed on index cards and remember the last word of each sentence in the order presented for later recall. Following each production the printed sentence was removed and the subject stated whether the sentence was true (T) or false (F) and another sentence was immediately presented until the set was completed. Sets ranged from 2 to 6 sentences in length. At the end of each set, the subject was asked to recall the last word of each sentence. There were 3 items at each set size and all items were presented to each subject. Sample items at each set length are presented in Table 2. Two scores were obtained for each subject.

"Words Recalled": The number of words recalled in the correct serial position with a correct true/false judgment. Scores could range from 0 to 60.

"Longest Series": The longest sentence set in which all final words were correctly recalled for at least 1 out of 3 trials. Scores could range from 2 to 6.

All participants in the CI group and half of the participants in the NH group were tested by the same examiner. Due to illness of this examiner, 23 of the NH participants were tested by another examiner who was trained in the procedure and observed the first examiner administering the test to several subjects.

Articulation Rate

Each student's repetitions of the McGarr Sentences[15] were audio-recorded for analysis of their speech production skills [16]. The duration of each utterance was measured in milliseconds and duration measures were obtained for all sentence repetitions whether or not they were repeated correctly. Average duration of the 7-syllable sentences was used to estimate articulation rate and as a proxy for verbal rehearsal speed[17].

Speech Perception

Several speech perception tests were administered to children in the CI group, including the Lexical Neighborhood Test of monosyllabic word recognition [1], the BKB sentence test [2], and the Children's Auditory Visual Enhancement Test [3]. Because results on these tests were highly correlated, they could be reduced to a single speech perception factor score through principal components analysis [4]. These scores were used to represent speech perception skill in all of the analyses conducted here.

Language

Language was represented by standard scores on the Peabody Picture Vocabulary Test (PPVT)[5], a wide-ranging individually administered receptive vocabulary measure.

Reading

Reading was represented by the Test of Reading Comprehension (TORC) [6], a silent reading test in which the student reads paragraphs and answers 5 multiple choice questions about each paragraph. Questions require both recalling story details and making inferences from the information presented.

Results

Digit Span

Individual "scaled scores" on the Digit Span subtest of the WISC-III are presented in Figure 1 for the 112 CI subjects. The average scaled scored on the Digit Span subtest of the WISC was 6.4 (SD = 2.5), more than one standard deviation below the NH mean for the normative sample (i.e., Mean SS = 10; SD = 3.0). Only 9 of the 112 students achieved scaled scores that were at or above the normative mean, indicating that most of these children exhibited shorter STM spans than their hearing age-mates. The mean number of digits forward (DSF) recalled by CI subjects was 5.3 (SD = 1.0) compared to 6.8 for NH peers. The mean number of digits backward (DSB) was 3.9 (SD = 0.9), compared to 5.0 for NH age-mates. Digit Span, representing the phonological loop that is used for the temporary storage of verbal phonological memory codes, is delayed in these teenagers, likely due to reduced auditory input through a CI compared to NH individuals.

Reading Span

T-F judgments of semantic acceptability of sentences averaged over 98% correct in both CI and NH groups, indicating excellent reading comprehension in both groups. Group means for CI and NH subjects are shown in Figure 2 for longest series and in Figure 3 for words recalled. Results for the entire NH group are displayed next to results for half of the NH group tested by the same examiner as the CI group. There were significant "examiner differences" within the NH group. When data from all 46 NH subjects are considered (two examiners) the CI group obtained significantly higher mean scores than the NH group. When only subjects who were all tested by the same examiner are considered (one examiner) no differences were found between CI and NH groups. Figure 2 shows that the average longest series score for the 112 CI subjects was 4.4 (SD= 1.1) which was significantly longer than for the 46 NH Subjects (M= 3.6; SD = 1.1) (F (1, 156) = 15.7; p<.001). Figure 3 shows that the average words recalled score for the 112 CI subjects (M = 35.9; SD = 10.4) was significantly higher than for the NH group (M = 28.6; SD = 12.4) (F (1, 156) = 14.1; p = .0002). However, when only scores from those 23 NH subjects and 112 CI subjects tested by the same examiner are compared, the mean scores are practically identical. Figure 4 summarizes the mean number of sets correct (out of 3 possible) at each sentence length for the CI and NH participants who were tested by the same examiner. No group differences were observed at any sentence span length. CI students performed as well or better than their NH age-mates on all components of the Reading Span task. Reading span, representing a domain-general central executive that controls attention and processing activities and regulates the flow of information in the processing system, is essentially normal in these teenagers with CIs.

Articulation Rate

Individual average durations (in milliseconds) of each CI student's productions of the 7-syllable McGarr sentences is summarized in Figure 5 in relation to the range of durations observed in the sample of 46 NH control subjects. A little over half of the CI group (55%) produced sentence durations that were within the range observed in NH age-mates but 39% were slower and the average duration for the CI group (2024 msec, SD =461)) was significantly slower than the durations of the NH group (1777 msec. SD = 162) (F (1,154) = 12.6; p <.001). Slower verbal rehearsal speed limits the capacity of the phonological loop to maintain information in verbal STM as evidenced by shorter digit spans in the CI subjects.

Predicting Language and Reading Scores in Teenagers with CIs—Multiple regression analysis was used to examine the relative contribution of articulation rate, forward digit span, backward digit span and reading span scores to language (PPVT) and reading (TORC) outcomes after variance due to speech perception (LNT) was removed. Backward digit span was subsequently deleted from the model because it did not contribute significant variance to either language or reading outcomes when reading span was included (likely because both are measures of WM capacity). Results are summarized in Table 3 for predicting language outcome and Table 4 for predicting reading outcome. Table 3 indicates that speech perception, articulation rate, forward digit span and sentence span each contributed independently to language outcome, together accounting for 43% of total variance. Table 4 indicates that articulation rate and reading span independently accounted for 34% of the variance in reading outcome score.

Discussion

This report provides results for the largest sample of CI-users to date to be tested on complex reading span, a widely-accepted measure of WM and central executive function. Surprisingly, in spite of their documented deficiencies in phonological processing in STM as exhibited on digit span tasks as well as slower verbal rehearsal speed as evidenced by articulation rate, these CI students performed at or above their NH age-mates on a reading span task, a complex WM measure. It would be theoretically interesting to test complex working memory in CI children using those same reading span stimuli in a listening condition. A direct comparison of these conditions could confirm whether performance is modality-specific in those deaf children with early onset hearing loss, a finding that is

NIH-PA Author Manuscript

NIH-PA Author Manuscript

contrary to reports that WM performance is modality independent in populations with NH[3]. The finding that visual reading span correlated significantly with backward digit span, a measure of WM in the auditory modality, suggests that similar processing skills underlie both tasks, but performance on the visual reading span task is not limited by compromised sensory input.

It has been reported that the reading span task is especially vulnerable to differences in stimulus presentation [1] . For example, delays between stimulus presentations may permit rehearsal of to-be-remembered items, making reading span more a measure of STM storage than of WM. Such differences may have contributed to significantly lower reading span scores in the 23 NH subjects tested by the second examiner. Nevertheless, in comparisons that included or excluded the second examiner, there was no evidence that these long-term CI users were delayed in complex WM span using visual sensory input. Even though CI participants experienced degraded and underspecified auditory input that only partially restored normal speech perception skills (i. e, they only understood about half of words presented through listening alone), their ability to perform a complex verbal memory span task using visual input and reading was not impaired. We found that digit span, requiring use of the auditory phonological loop, reflected deficiencies in CI adolescents compared to individuals with normal hearing.

The language and reading demands of the reading span task were well within the capability of all of these teenagers, as evidenced by their high degree of accuracy in true-false judgments. However, their WM capacity accounted for significant variance in predicting both language and reading outcomes. While vocabulary development was influenced by both forward digit span (auditory STM) and articulation rate (verbal rehearsal speed), when these factors were controlled, it was those students who could store and retrieve final words from larger sentence sets who exhibited the strongest language skills. In the case of reading, students with faster articulation rates were also the better readers, but among those with similar phonological rehearsal speeds, it was those with the longest WM spans who achieved the highest reading scores.

The concepts of short term and working memory capacity, the phonological loop and speed of verbal rehearsal are derived from seminal studies in cognitive psychology[1, 2, 18, 19]. These are useful constructs for explaining variability in development of language and reading skills in children who use cochlear implants. Further study is needed to determine how fluid intelligence, as reflected in WM capacity, helps children to compensate for the effects of early profound hearing loss on verbal development and allows some of them to catch up with hearing age mates in language and reading skills during their school years.

Acknowledgments

This research was supported by Grant No. DC008335 from the National Institute on Deafness and other Communication Disorders (NIDCD). The reading span task was adapted for this study by Gloria Waters, Ph.D , who also conducted examiner training. We wish to thank the teenagers and their families whose enthusiastic participation made this project possible. We also thank examiners Joyce Saffa, Karen Kupper, and Mary Gamache.

Funding: This work was supported by the National Institute of Deafness and Other Communication Disorders (NIDCD) RO1 DC008335.

Reference List

(1). Conway AR, Kane MJ, Bunting MF, Hambrick DZ, Wilhelm O, Engle RW. Working memory span tasks: A methodological review and user's guide. Psychon Bull Rev. 2005; 12(5):769–786. [PubMed: 16523997]

(2). Baddeley A, Gathercole S, Papagno C. The phonological loop as a language learning device. Psychol Rev. 1998; 105(1):158–173. [PubMed: 9450375]

(3). Daneman M, Carpenter P. Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior. 1981; 19:450–466.

(4). Stiles D, McGregor K, Bentler R. Vocabulary and working memory in children fit with hearing aids. Journal of Speech, Language and Hearing Research. 2012; 55:154–167.

(5). Watson D, Titterington J, Henry A, Toner J. Auditory sensory memory and working memory processes in children with normal heairng and cochlear implants. Audiology Neurotology. 2007; 12:65–76. [PubMed: 17264470]

(6). Pisoni D, Kronenberger W, Roman A, Geers A. Measures of digit span and verbal rehearsal speed in deaf children with more than 10 years of cochlear implantation. Ear and Hearing. 2011; 32(1): 60S–74S. [PubMed: 21832890]

(7). Kirk K, Pisoni D, Osberger M. Lexical effects on spoken word recognition by pediatric cochlear implant users. Ear Hear. 1995; 16(5):470–481. [PubMed: 8654902]

(8). Geers AE, Tobey EA, Moog JS. Editorial: Long-term outcomes of cochlear implantation in early childhood. Ear Hear. 2011; 32(1 Suppl):1S. [PubMed: 21832884]

(9). Wechsler, D. Wechsler Intelligence Scale for Children. Third ed. Psychological Corporation; San Antonio: 1991.

(10). Dunn, L.; Dunn, L. Peabody Picture Vocabulary Test. Revised ed. American Guidance; Circle Pines, MN: 1981.

(11). Brown, V.; Hammill, D.; Wiederholt, J. Test of Reading Comprehension. 3rd ed. Pro-Ed; Austin, TX: 1995.

(12). Geers AE, Sedey AL. Language and verbal reasoning skills in adolescents with 10 or more years of cochlear implant experience. Ear Hear. 2011; 32(1 Suppl):39S–48S. [PubMed: 21832889]

(13). Geers AE, Hayes H. Reading, writing, and phonological processing skills of adolescents with 10 or more years of cochlear implant experience. Ear Hear. 2011; 32(1 Suppl):49S–59S. [PubMed: 21258612]

(14). Geers AE, Brenner CA, Tobey EA. Long-term outcomes of cochlear implantation in early childhood: sample characteristics and data collection methods. Ear Hear. 2011; 32(1 Suppl):2S–12S.

(15). McGarr N. The intelligibility of deaf speech to experienced and inexperienced listeners. Journal of Speech, Language and Hearing Research. 1983; 26:451–458.

(16). Tobey EA, Geers AE, Sundarrajan M, Shin S. Factors influencing speech production in elementary and high school-aged cochlear implant users. Ear Hear. 2011; 32(1 Suppl):27S–38S.

(17). Pisoni D, Cleary M. Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. Ear and Hearing. 2003; 24(Supplement):106–120.

(18). Gathercole S. Cognitive approaches to the development of short-term momory. Trends in Cognitive Science. 1999; 3:410–418.

(19). Hulme C, Thomson A. Speech rate and the development of short-term memory span. Jurnal of Experimental Child Psychology. 1984; 38(2):241–253.

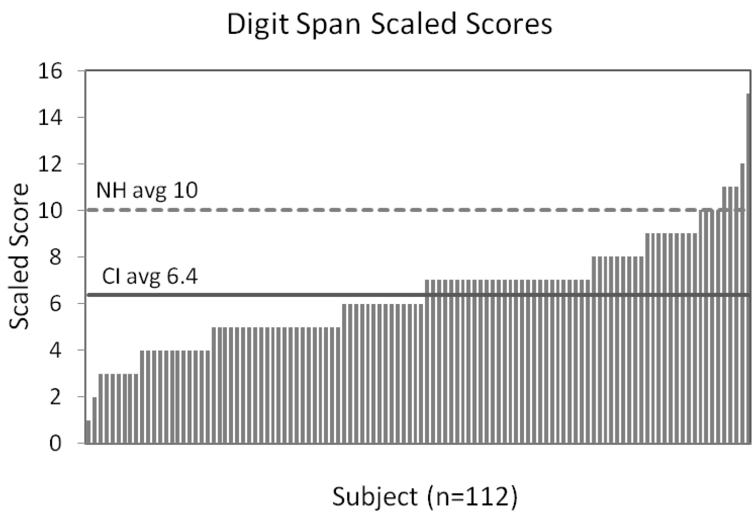

Figure 1.
Columns represent scaled scores on the Digit Span subtest of the Wechsler Intelligence Scale for Children for 112 adolescent cochlear implant (CI) users. Standardized scores express performance relative to the mean (i.e., 10) and standard deviation (i.e., 3) for the normative sample of normal hearing (NH) peers. The CI mean of 6.4 is more than one standard deviation below the normative sample mean.

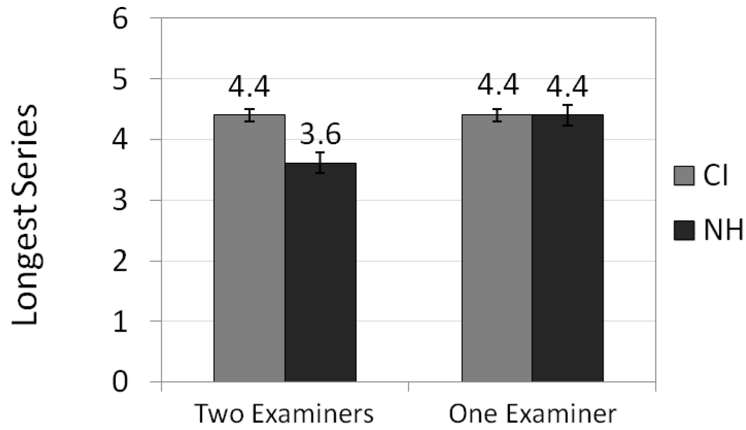

Figure 2.
Mean number of words recalled in the correct serial position with a correct true/false judgment is represented for CI and NH subjects. Results for 112 CI subjects are compared with two different NH groups: "Two examiners" includes all 46 subjects, 23 of whom were tested by the same examiner as the CI group and 23 of whom were tested by a different examiner. "One examiner" includes only those 23 NH subjects who were tested by the same examiner as the CI group.

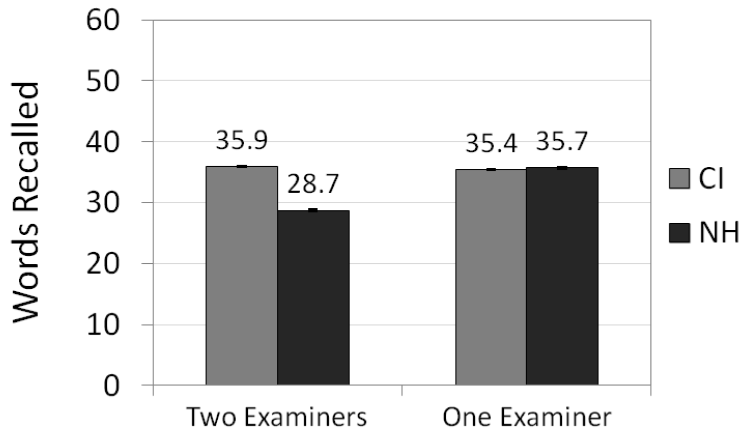

Figure 3.
Mean longest sentence set in which all final words were correctly recalled for at least 1 out of 3 trials is represented for CI and NH subjects. Results for 112 CI subjects are compared with two different NH groups: "Two examiners" includes all 46 subjects, 23 of whom were tested by the same examiner as the CI group and 23 of whom were tested by a different examiner. "One examiner" includes only those 23 NH subjects who were tested by the same examiner as the CI group.

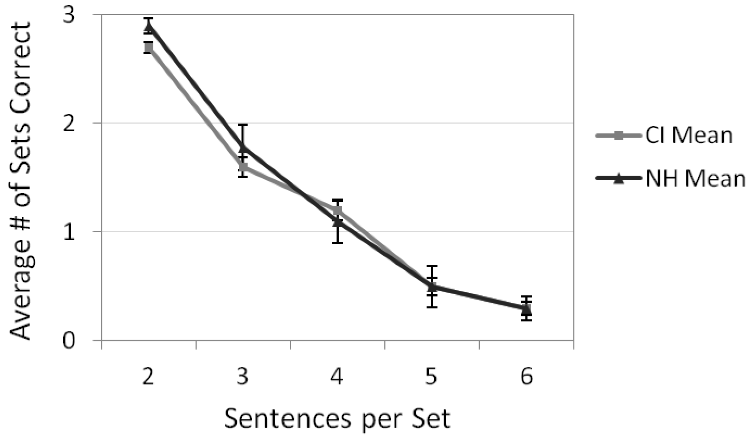

Figure 4.

Average number of sentence sets for which all final words were correctly recalled is plotted for each set length for CI (N= 112) and NH (N=26) teenagers who were all administered the reading span task by the same examiner.

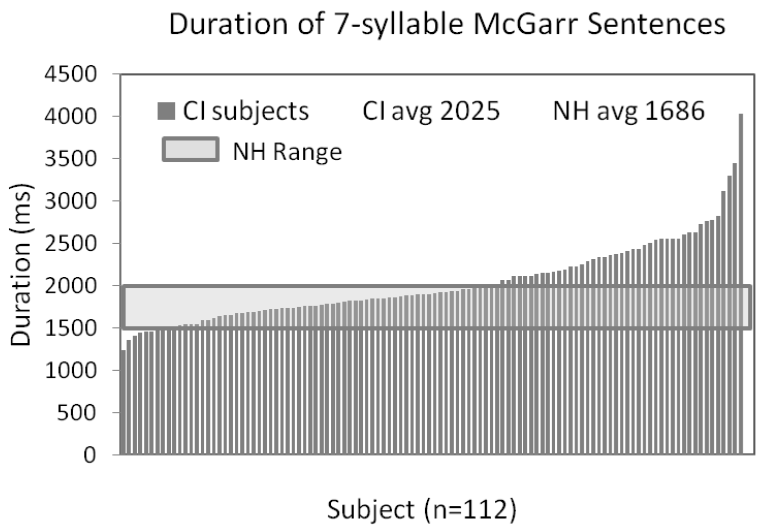

Figure 5.

Average duration, in msec, of each CI student's production of 7-syllable sentences is represented by ordered columns. Durations in 60 CI participants are compared to the range of average duation for 46 NH age-mates, represented by the shaded area.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 1

Subject Characteristics

Variable	CI students (N=112) Mean	SD	Range	NH Students (N=46) Mean	SD	Range
Age	16.7	0.64	14.9-18	16.6	0.84	15.0-18
Parent Education (years)	16.0	2.4	12-20	16.9	2.3	12-20
% Female	52.7%	-	59 F, 53 M	52.2%	-	24 F, 22 M
Receptive vocb **	90	22.6	40-160	109.6	9.2	88-128
Reading vocab ***	9.0	2.5	2-13	10.6	1.8	2-12
Reading comp ***	7.6	2.6	3-13	10.1	2.4	4-15

•Children's non-word repetition test: percent words correct

** Peabody Picture Vocabulary Test: Standard Score (normative mean = 100; SD = 15)

*** Test of Reading Comprehension: Scaled Score (normative mean = 10; SD = 3)

Table 2

Reading Span Test for Children – Adapted from Daneman and Carpener (1980): Sample Items at Each Set Length

Sets	Example
2 Sentence Set	• A lemon is a yellow fruit. • In the summer the grass is pink.
3 Sentence Set	• At night it is very dark. • Most dogs like to eat bones. • A peach is a fruit that is salty.
4 Sentence Set	• If you are blind you cannot hear. • When you are sick you feel bad. • You sit down to drive a car. • Most people have two arms.
5 Sentence Set	• An elephant makes a good pet. • There are three days in a week. • People go to church on Sunday. • Fish is something that you drink. • You go to bed to go to sleep.
6 Sentence Set	• A pet dog needs food and water. • When it rains the roads are dry. • Some cars are made of brick. • Baseball is a game that is played inside. • Most cars have three wheels. • A baby sleeps in a crib.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 3

Regression Predicting Language (PPVTss)

Measure	Coefficient	t-value	Significance	R^2
Speech Perception	0.18	2.01	.05	
Articulation Rate	−0.39	−4.42	.000	
Forward Digit Span	0.19	2.15	.03	
Reading Span	0.16	2.15	.03	
Total Explained Variance				*0.43*

Table 4

Regression Predicting Reading (TORC avg SS)

Measure	Coefficient	t-value	Significance	R^2
Speech Perception	−0.06	−0.59	NS	
Articulation Rate	−0.42	−4.41	.000	
Forward Digit Span	0.13	1.37	NS	
Reading Span	0.30	3.66	.000	
Total Explained Variance				*0.34*