

NEUROCOGNITIVE CORRELATES OF SPECTRALLY-DEGRADED SPEECH
RECOGNITION IN CHILDREN

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NEUROCOGNITIVE CORRELATES OF SPECTRALLY-DEGRADED
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The research reported in this dissertation was carried out to investigate the contribution of several core neurocognitive factors in speech perception when degraded and underspecified phonological and lexical representations of speech are presented to normal-hearing (NH) listeners. The first study successfully replicated Experiment 2 from Eisenberg, Martinez, Holowecky, and Pogorelsky (2002), which demonstrated the influence of word frequency and neighborhood density on recognition of vocoded speech.

The second study assessed relations between vocoded sentence perception and measures of auditory attention and short-term memory in NH children. Analyses revealed significant relations between performance on both sets of neurocognitive measures and vocoded speech perception tasks. These findings support the hypothesis that vocoded speech perception reflects not only peripheral processes, but cognitive processes as well.

The third study used the California Verbal Learning Test – Children’s Edition (CVLT-C) to examine relations between verbal learning in memory and speech perception. In the first part, NH children were assessed on the CVLT-C and vocoded speech. In the second part, we investigated relations between speech perception and the CVLT-C in a group of children with cochlear implants (CI) and NH age-matched controls. Findings from this study revealed that that CI children and NH children processed verbal material in fundamentally different ways in a multi-trial free recall learning task.

Taken together, these studies provided new insights into the foundational underlying neurocognitive processes that support perception of spectrally-degraded speech in children – an area of research previously unexplored—and established the need for extending future research in hearing impaired children with cochlear implants to include new measures of cognition such as attention, verbal learning, and memory.

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CHAPTER 1

INTRODUCTION: NEUROCOGNITIVE CORRELATES OF SPECTRALLY-DEGRADED SPEECH RECOGNITION IN CHILDREN

Speech perception abilities in normal-hearing (NH) typically-developing children begin to develop prenatally and quickly improve after birth. With minimal exposure to language, infants show evidence of categorical perception of speech sounds, adapting also to variability of speech by multiple talkers and variability in speaking rate (Jusczyk, 1997). After more exposure, infants begin to segment words in speech in their native language and demonstrate statistical learning abilities along with other more complex forms of speech perception all before one year of age (Jusczyk & Luce, 2002). This rapid development of speech perception abilities is essential for the growth of spoken language, which is critical for successful cognitive and social development in children. Delays in speech perception development are associated with a number of developmental risks including poor reading abilities (Mody, Studdert-Kennedy, & Brady, 1997), dyslexia (Boets, Ghesquière, Van Wieringen, & Wouters, 2007; Manis et al., 1997; Richardson, Leppänen, Leiwo, & Lyytinen, 2003), and poorer language comprehension (word and phrase understanding) and production (word production) (Tsao, Liu, & Kuhl, 2004).

Hearing impairments delay and in some cases disrupt and reorganize the normal time course of speech and language development. Without prenatal and early exposure to sound, deaf and hard-of-hearing children begin life already developmentally delayed relative to their normal-hearing peers. Although deaf and hard-of-hearing children can now be implanted with cochlear implants to restore acoustic input to the auditory system, the acoustic information they receive via the cochlear implant is spectrally-degraded so it

is not as rich or detailed as the information being conveyed to a normal-hearing system. Especially because deaf children are receiving cochlear implants and are fit with hearing aids earlier than ever, new research is needed to better understand the development of speech recognition skills in this clinical population and the variability in speech and language outcomes after cochlear implantation.

One approach to understanding how the processing of speech through a cochlear implant affects speech recognition has been through the use of spectrally-degraded vocoded speech with NH listeners. Spectrally-degraded speech refers to speech signals that have been processed to preserve gross temporal and amplitude information but have degraded fine spectral information in the signal (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). This type of noise-vocoded speech was created by Shannon et al. (1995) to model the speech produced by a cochlear implant. First, speech is divided into a designated number of frequency bands, or spectral “channels.” Next, the amplitude envelope is extracted from each frequency band, which preserves the temporal components of the speech signal. Lastly, using the profiles of the amplitude envelopes, white noise is added to each frequency band and then combined with the other frequency bands to create a newly vocoded signal.

One fundamental gap in our knowledge regarding the perception of spectrally-degraded speech is understanding how NH children perceive vocoded speech. The use of spectrally-degraded speech allows researchers to replicate the hearing experience produced by cochlear implants in NH children who have typically-developed cognitive systems. Understanding how the NH children perceive vocoded speech provides researchers with information on the effects of reduced acoustic information in the speech

signal on spoken word perception while eliminating confounding factors related to hearing loss. Currently, very little research has used vocoded speech with NH children and what little there is has focused on the sensory and perceptual requirements for vocoded speech perception.

In a seminal study, Eisenberg, Shannon, Martinez, Wygonski, and Boothroyd (2000) first used vocoded speech with NH children to evaluate performance on speech recognition tasks while varying the amounts of spectral information available in the signal. Perceptual data obtained from two groups of children (young: 5-7 years; old: 10-12 years) and a group of adults revealed significantly lower performance by younger children when the amount of fine spectral information in the signal was reduced. Older children and adults did not significantly differ leading the authors to conclude that younger children require more spectral information in the signal to accurately identify spoken words and sentences. This suggests that there might be a critical component of speech perception that has not fully developed and/or is less efficient in young children. Identifying this component could potentially provide important insight into identifying children at risk for delays in the development of speech perception abilities. For example, in a speech recognition task using the HINT-C sentences, Eisenberg et al.'s (2000) younger group recognized an average of 82% of the sentences correctly in the 8-channel condition while the older children and adults recognized 93% and 94%, respectively. Although the amount of spectral information varied from 4-32 channels, performance for all groups tended to plateau when more than 8 channels of information were provided. This finding was consistent with later studies investigating the amount of spectral information needed for spoken word recognition (Dorman, Loizou, Kemp, & Kirk, 2000),

talker identification (Vongpaisal, Trehub, Schellenberg, & van Lieshout, 2012), and audiovisual integration (Maidment, Kang, Stewart, & Amitay, 2014).

While it has been demonstrated that younger children require more information for reliable vocoded speech recognition, this finding was only observed in children five and older. To understand how even younger children perceive vocoded speech, Newman and Chatterjee (2013) tested toddlers in a preferential looking study to assess how well they could discriminate between two vocoded words with different amounts of spectral information available. They found that toddlers looked at the target object significantly longer (above chance performance) for the unprocessed, 8- and 24-channel conditions; however, they were slower to respond to the correct target object as the amount of spectral information was reduced. When the vocoded speech was reduced to 2 and 4 channels, the majority of children performed the task at below chance levels. Like the older children, toddlers need at least 8 channels of spectral information to accurately respond to a target signal.

In another study by Warner-Czyz, Houston, and Hynan (2014), 6-month-old infants were tested on vocoded vowel discrimination with varying numbers of spectral channels (unprocessed, 16, and 32 channels) using a visual-habituation task. The authors found that infants needed at least 32 channels to discriminate between the consonant-vowel syllables /ti/ and /ta/. This finding is in line with other studies reporting a strong relationship between age and amount of spectral information needed to accurately recognize speech.

The use of vocoded speech is important because it can help us better understand the effects of degraded auditory input in individuals with cochlear implants without any

interactions from cognitive or perceptual consequences related to hearing loss. This research would also contribute to the basic science of speech perception because it provides real-world ecological scenarios for when speech is degraded before ever entering the auditory system (e.g. acoustic transmissions by cell phones or over FM systems). Researchers can then utilize knowledge on how a NH typically-developed system perceives and encodes degraded acoustic information to efficiently identify potential developmentally at-risk children with cochlear implants and develop effective interventions. For example, vocoded speech has been used in studies to compare performance of NH children to children with cochlear implants. Conway, Walk, Deocampo, Anaya, and Pisoni (in press) used vocoded speech to investigate the role of sentence context in word recognition in NH children listening to vocoded speech compared to children with cochlear implants listening to unprocessed speech. The authors found that when asked to recognize vocoded spoken sentences, NH children utilized sentence context more effectively than children with cochlear implants. Another study by van Heugten, Volkova, Trehub, and Schellenberg (2013) used familiar cartoon voices to examine a child's ability to identify different talkers. The stimuli were vocoded for NH children but unprocessed for children with cochlear implants. The NH children heard voices that differed in spectral degradation ranging from 4-24 channels. Using a forced-choice task, even with the fewest number of channels, the NH and children with cochlear implants were able to identify familiar cartoon voices at above chance performance, although children with cochlear implants did slightly poorer, on average, on this task. The authors suggest that the findings from this research demonstrate the possibility of talker recognition even when temporal fine structure is absent from the

speech signal because the children are able to utilize articulatory timing differences in the cartoon character's voices as a result of long-term representations of these voices in memory.

One study of particular importance to the present research was carried out by Eisenberg, Martinez, Holowecky, and Pogorelsky (2002). Eisenberg et al. (2002) investigated the effects of word frequency and neighborhood density on vocoded spoken word and sentence recognition using a small group of NH children 5-14 years in age. The authors found that lexically "easy" words (high frequency words in English with fewer phonetically similar neighbors) were recognized better in both isolation and in sentences than lexically "hard" words (low frequency words with more phonetically similar neighbors). Eisenberg et al. (2002) also found that accuracy for words in sentences was better than for the same words in isolation (i.e., context benefit gain). While this study is frequently cited in the literature on the perception of vocoded speech in children, no follow-up research has ever been conducted despite the importance of the problem and several significant limitations in the original study.

One limitation of the Eisenberg et al. (2002) study was the very small sample size for the age-range tested. The study used only 12 normal-hearing children ranging from 5-14 years in age with an uneven distribution of participants across ages. Moreover, three of the children included in the sample had receptive vocabulary scores below their age-equivalencies, which may present a problem when interpreting results of analyses on the effects of receptive vocabulary on vocoded speech perception measures.

The study by Eisenberg et al. (2002), like most studies of vocoded speech perception in children, also did not include any neurocognitive measures even though

earlier research findings have shown that auditory perception in children is associated with a range neurocognitive processing operations. The addition of neurocognitive measures could have provided more insight into individual differences in performance. For example, performance on a number of auditory processing tasks, including pitch discrimination and temporal order discrimination of tones, is positively correlated with measures of verbal and nonverbal intelligence in children (Deary, 1994). We also know from earlier research that children with cochlear implants often show significant delays and deficits in several areas of cognition such as: working memory (Burkholder & Pisoni, 2003; Pisoni, Kronenberger, Roman, & Geers, 2011), verbal short-term memory (Harris et al., 2013), language and reading (Johnson & Goswami, 2010), implicit sequence learning (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011) and theory-of-mind (Peterson, 2004).

Research with cochlear-implanted children suggests that speech perception and cognition are not parallel independent abilities but are closely coupled and linked together in development (e.g. Beer, Kronenberger, & Pisoni, 2011). What we have yet to understand is if this strong coupling also applies to development in NH children and how it may be affected by highly degraded spectrally-reduced speech. This is important to know because if speech perception and cognition are closely linked in development future research needs to be designed so that the focus is not just on one part of the speech perception process (either speech perception or cognition) but made to incorporate both. The more information that is available to researchers regarding speech perception development, the more targeted the interventions can be for children at risk for deficits or delays. Currently, the primary use of vocoded speech has been to assess how much

spectral information is needed by a listener to accurately understand the effects of poor spectral information on speech recognition. Using neurocognitive measures combined with vocoded speech perception tasks to find underlying relations between measures will help to identify which neurocognitive processes are involved in processing degraded speech. With that knowledge, we can improve our ability to provide process explanations for variability in performance in processing degraded speech. We also need to understand the role of more basic neurocognitive processes such as learning, attention, and memory in perceiving degraded speech to be able to identify and potentially intervene when children with cochlear implants are performing poorly.

The research reported here was carried out to investigate the contribution of several core neurocognitive factors in speech perception when degraded and underspecified phonological and lexical representations of speech are presented to listeners. More specifically, the purpose of this research was to understand the relations of cognition to vocoded speech perception in NH children, particularly the contribution of auditory attention, short-term memory, and verbal learning and memory. Investigating the links between vocoded speech perception and cognition in NH children will provide researchers with new basic knowledge about the operations of the information processing system of deaf children with cochlear implants that are used to encode, store, process and use spoken language as well as with new knowledge about how children process speech in suboptimal listening conditions. This knowledge will enable clinicians and researchers to better understand individual differences in deaf children with cochlear implants. By identifying the factors that underlie a successful listener it will allow us to understand the effects of spectrally degraded underspecified acoustic representations on the processing

and encoding of speech. This knowledge will also be beneficial for normal-hearing children to understand the effects of listening to speech in adverse listening conditions.

No research has examined the core underlying neurocognitive processes involved in perceiving vocoded speech in children. Thus, this research fills in a significant gap in our understanding of the role of neurocognitive factors in speech perception and spoken language processing. For the purpose of this research, two specific cognitive processing domains were assessed in NH children: attention and memory. In particular, auditory attention, short-term memory, and verbal learning and memory were assessed in a group of children 5-13 years of age. Their performance was also compared to a group of young adults.

Attention, as it pertains to this research, refers to the properties of cognition involving control and allocation of limited processing resources and capacities (*controlled* attention, as opposed to attention as a basic perceptual process (Cowan, 1995)). Attention operates to keep information active in memory during a wide range of cognitive processes. Auditory attention, most relevant to this research, specifically refers to preferential focus directed at specific auditory information and keeping auditory information active in memory. Auditory attentional processes select what information is processed further by other cognitive systems which makes it essential for efficient information processing in speech and language tasks (Gomes, Wolfson, & Halperin, 2007). Auditory attention was chosen as a cognitive measure because it is how information is selected for further processing by the auditory system and if a child's ability to inhibit irrelevant information from being processed is ineffective it could negatively impact the ability to accurately recognize degraded speech.

Short-term memory refers to a subsystem that stores limited amounts of information for a short period of time (Baddeley, 2012; Cowan, 2008; Unsworth & Engle, 2007). Short-term memory has a well-established role in speech perception and language acquisition because it controls verbal rehearsal and storage of information while long-term representations are created in memory (e.g. Baddeley, Gathercole, & Papagno, 1998; Frankish, 1996; Jacquemot & Scott, 2006; Peter W Jusczyk, 1997; Pisoni, 1975). Short-term memory was chosen as a cognitive measure because if short-term memory is impaired then it could prevent the accurate encoding of verbal information for transfer into long-term memory, which aids in spoken word recognition.

Lastly, measures of verbal learning and memory using the California Verbal Learning Test- Children's Edition (CVLT-C) were obtained. The CVLT-C is a valuable neuropsychological assessment tool that provides information regarding how an individual learns and recalls verbal information over a short period of time using an ecologically valid memory task. The CVLT-C is often used in clinical settings to detect and diagnose memory impairments that may be related to additional learning or neurological disorders (Delis, Kramer, Kaplan, & Ober, 1994). Although the CVLT-C is primarily used with clinical populations, it provides valuable information regarding learning strategies, memory capacity, and effects of interference in a relatively short amount of time, which could provide new insights into and a more in-depth understanding of the core cognitive factors that affect the perception of degraded speech. Taken together, this research was designed to understand some of the underlying neurocognitive processes used in perceiving vocoded speech in children.

The following four chapters summarize the findings of the investigation into neurocognitive predictors of vocoded speech. Chapter 2 reports the results of a replication and extension of Eisenberg et al.'s (2002) vocoded speech study with NH children and adults. In Chapter 3, auditory attention and short-term memory are examined as possible predictors of vocoded speech recognition in children. Chapter 4 investigates the role of verbal learning and memory using the California Verbal Learning Test- Children's Version (CVLT-C) as a predictor of vocoded speech recognition in NH children and adults. Data are also reported for a group of children with cochlear implants and age-matched NH controls also using the CVLT-C. Lastly, Chapter 5 provides a final summary, conclusions, and potential applications of the research findings.

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CHAPTER 2

VOCODED SPEECH RECOGNITION IN NORMAL-HEARING CHILDREN USING LEXICALLY CONTROLLED WORDS AND SENTENCES: A REPLICATION AND EXTENSION

Introduction

Spoken word recognition is a remarkable ability in normal-hearing listeners. Normal-hearing listeners can successfully recognize speech even when the signal is not ideal, such as when it is in the presence of background noise, the signal is degraded (for example, by phone or radio transmission), or when there is a large variability in talkers (e.g. accents, age, or gender). Recognition begins when a spoken word is conveyed to a listener in the form of a complex sound wave. The signal is then perceived physiologically and neurologically by the components of the outer, middle, and inner ear. From there, the signal is transmitted to the brain where it is interpreted in a linguistic and psychological manner. In hearing-impaired individuals, this chain of events is disrupted and often significantly impaired resulting in poorer speech recognition abilities (Niparko, 2009). Because of the involvement of many factors, including severity of hearing loss and age at onset of hearing loss, enormous variability in speech and language outcomes is routinely observed in hearing-impaired individuals, especially listeners who have received cochlear implants (Niparko et al., 2010; Sarant, Blamey, Dowell, Clark, & Gibson, 2001; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). One core area of particular interest has always been variability in spoken word recognition processes

(Eisenberg, Martinez, Holowecky, & Pogorelsky, 2002; Grieco-Calub, Saffran, & Litovsky, 2009; Kirk, Pisoni, & Osberger, 1995; Svirsky et al., 2000).

Outside of the physiological limitations, linguistic difficulty with spoken word recognition can be understood within the framework of the Neighborhood Activation Model (NAM) developed by Luce and Pisoni (1998). NAM is a spoken word recognition model that explains the process of lexical discrimination and selection based on the similarity between the phonetic-acoustic properties of spoken words. These core acoustic-phonetic properties are conceptualized in terms of similarity neighborhoods. A similarity neighborhood is defined as a group of words that is phonetically similar to a target word. Each neighborhood can be characterized in terms of two properties: (1) lexical density and (2) word frequency. Lexical density reflects the degree of confusability of the words in a similarity neighborhood based on a one-phoneme substitution, addition, and deletion parameter (Luce & Pisoni, 1998). Frequency refers to the frequency of the words in the English language within a similarity neighborhood. Words in lexical neighborhoods are phonetically similar to the target word and differ by only one phoneme.

According to NAM, when a word is heard it activates other words with similar acoustic-phonetic properties in long-term memory. Words with the most similar patterns have higher levels of activation and, as the word is processed further, the words with continued similar patterns receive activation while less similar words lose activation. Words that are more frequent in the language show a stronger bias for probability of selection by the listener. Consequently, words are more easily identified if their

neighborhoods consist of high frequency words and lower densities compared to low frequency words from high-density neighborhoods (Luce & Pisoni, 1998).

Individuals with hearing impairment receive poorer acoustic-phonetic information from spoken words, which may result in their lexicon being organized into larger neighborhoods with increased densities (Bell & Wilson, 2001; Charles-Luce & Luce, 1990; Dirks, Takayana, & Moshfegh, 2001; Dirks, Takayanagi, Moshfegh, Noffsinger, & Fausti, 2001). Because of increased competition among similar-sounding words, spoken word recognition is significantly more difficult. Spectrally-degraded speech, or vocoded speech, has become an important tool for understanding the effects of hearing impairment on speech perception and spoken word recognition, especially in individuals with cochlear implants. Vocoded speech allows researchers to test hypotheses in normal-hearing populations without interference from confounding variables that are often difficult to control in clinical populations (e.g. etiology of hearing loss, surviving neural population, and duration of deafness).

Eisenberg et al. (2002) used the principles of NAM to investigate spoken word recognition in children with normal hearing and with cochlear implants. Their research had three specific objectives: 1) To determine if the lexically controlled words and sentences would display monotonic performance intensity functions (Experiment 1); 2) To test normal-hearing children under spectrally-degraded conditions on lexically controlled words and sentences replicating response patterns from the first experiment (Experiment 2); and 3) To test children with cochlear implants to assess if their response patterns replicated findings from the first two experiments (Experiment 3). For this research, we focused on their findings from the second experiment.

Eisenberg et al.'s (2002) second experiment investigated the effects of word frequency and neighborhood density on vocoded spoken word and sentence recognition using normal-hearing children 5-14 years in age. Speech recognition materials were generated using the principles of NAM and earlier research conducted by Kirk, Pisoni, and Osberger (1995) and Bell and Wilson (2001). Eisenberg and colleagues created sets of “easy” and “hard” words based on lexical density and word frequency. “Easy” words were high-frequency words selected from sparse neighborhoods and “hard” words were low-frequency words from dense neighborhoods. Results from Experiment 2 demonstrated that lexically “easy” words were recognized by normal-hearing children better than lexically “hard” words in both isolation and sentences under vocoded (degraded) conditions. They also found that accuracy for words in sentences was better than for the same words in isolation (context benefit gain). This particular study was important because it demonstrated the robustness of recognition patterns based on word frequency and neighborhood density in open-set word recognition when listeners received spectrally-degraded speech signals. This means that successful word recognition is not solely dependent on the quality of the speech signal, but on some underlying cognitive component facilitating recognition as well. Since the time this pioneering study was carried out, no attempts at replications have been made although this study is widely cited in the literature. One purpose of the present research was to carry out a replication of the findings from this study to assess how robust the original findings were. If the original study can be replicated, then it would strongly support the proposal for involvement of cognition in degraded spoken word recognition. In addition, the replication findings, specifically the context gain aspect, are important for

understanding the significance of the findings from Chapter 3 and Chapter 4 which investigate additional cognitive aspects of vocoded speech recognition. A second goal was to obtain a benchmark for further studies on the role of attention, learning, and memory in the perception of vocoded speech by children.

In the original study, Eisenberg et al. (2002) tested 12 normal-hearing children ranging from 5-14 years in age with an uneven distribution of participants across ages. Because the sample size is so small and covers a wide age range, the interpretation of the findings of the original study are limited because they could be easily influenced and biased by factors relating to age and development. The majority of children in the sample were not naïve to vocoded speech and three children had receptive vocabularies below their age-equivalencies. Some of the children were used in Experiment 1 of the original study and, therefore, had prior exposure to the materials, which might increase recognition performance in Experiment 2. Also, children with receptive vocabularies below their age-equivalencies could indicate language or developmental delays so they would not be appropriate to use since they are not representative of a typically-developed population. One purpose for replicating Eisenberg et al.'s (2002) experiment was to address these limitations. The present replication study tested 31 children over the same age range to increase the sample size to verify that the findings from original study were reliable. All the children used in the present study had receptive and expressive vocabularies within the normal range for their ages. Also, the original study did not include any measures of cognitive processing and this limitation will be addressed further in Chapters 3 and 4.

In addition to addressing several of the limitations of the original study, the present study extended Eisenberg et al.'s (2002) earlier study by including a vocoded speech familiarization task (WIPI), an expressive vocabulary test (EVT-2), and a group of adults that provided a baseline measure for performance. The closed-set Word Intelligibility by Picture Identification- 2nd Edition (WIPI) was chosen for the vocoded speech familiarization task because of its simplicity (closed-set design) and child-friendly stimuli. Completing this task prior to the other vocoded speech perception tasks gave the children time to adjust to a new form of speech and learn task instructions. The Expressive Vocabulary Test- 2nd Edition (EVT-2) was added to provide converging information regarding the role of vocabulary knowledge in vocoded speech perception. Lastly, adding a group of adults as a baseline group for comparison removed the contribution of development and linguistic experience. We collected pilot data to verify the replication was reproducible and also analyzed data from the original Eisenberg et al. (2002) study along with data from the current study to obtain measures of context benefit gain.

Methods

Part 1. Replication of Study 2 of Eisenberg et al. (2002)

Participants

Thirty-seven typically-developing monolingual English-speaking children (15 females, 22 males) from 5;2 years (years; months) to 13;3 years of age ($M=12;4$ years; $SD=2;7$ years) were recruited for this study. The majority of the sample was Caucasian ($n=33$), with the remaining identified as either Native Hawaiian/ Pacific Islander ($n=2$) or more than one race ($n=2$). Six children were excluded for the following reasons:

technical problems ($n=2$), noncompliance ($n=3$), and reported speech delays ($n=1$). Thus, 31 children between 5;9 years and 13;3 years of age ($M=10;0$ years, $SD=2;4$ years; 12 females, 19 males) were included in the final dataset. An independent samples t-test revealed that the children in the replication dataset did not significantly differ in age compared to the children in Eisenberg et al.'s (2002) study ($M=8;8$ years, $SD=2.67$); $t(41)=1.54, p=.13$. By parent-report, all children had normal hearing and vision and had no diagnosed cognitive/developmental delays. All children were recruited through an IRB approved departmental subject database. The majority of the children that participated in this study were from families with a moderate socioeconomic status: 19% reported incomes less than \$50,000; 58% reported incomes within the \$50,000-\$100,000 range; 6% reported incomes within the \$100,000-\$150,000 range; 10% reported incomes within the \$150,000-\$200,000 range; and 6% reported incomes greater than \$200,000. All children included in the final data analyses passed a pure-tone hearing screening at 15 dB between 250-4000 Hz to verify that their hearing was within normal limits.

Equipment

Speech perception testing occurred in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. A high-quality loudspeaker (Advent AV570) was located approximately two feet from the listener. A RadioShack Digital Sound Level Meter was used to verify stimulus presentation levels over loudspeaker at 65 dB using C-Weighting. Speech stimuli were presented using programs run on a Power Mac G4 Apple computer with a Mac OS 9.2 using Psyscript (Bates & D'Oliveiro, 2003).

Vocoded Stimuli

Spectrally-reduced speech signals were created by replicating the techniques

described in Shannon, Zeng, Kamath, Wygonski, and Ekelid (1995) and Eisenberg et al. (2002). Original recordings of the unprocessed speech stimuli were obtained from Dr. Laurie Eisenberg for the replication of Experiment 2 of the Eisenberg et al. (2002) paper. AngelSim (TigerCIS), an online cochlear implant speech-processing program, was used to custom-vocode all of the speech stimuli. The original set of speech signals was processed to 4 spectral channels with bandwidth frequencies set at 300, 722, 1528, 3066, and 6000 Hz using a noise-vocoded setting with white noise as the carrier type (see Table 2.1 for division of frequencies for each channel).

Performance Measures

Peabody Picture Vocabulary Test- 4th Edition (PPVT-4)

The PPVT-4 was used to obtain a measure of the child's receptive vocabulary. This test is a standardized vocabulary assessment that can be administered to participants ranging in age from 2.5-90+ years. During administration of the PPVT-4, the experimenter showed the child a page with four different colored illustrations displayed in a 2x2 box format. The experimenter said the stimulus word out loud and instructed the child to either point to or say the number associated with the picture that best illustrated the meaning of the word. Guessing was encouraged. The child began the PPVT-4 at a predetermined point based on the child's chronological age and continued until he or she reached ceiling on the assessment. The PPVT-4 contains a total of 228 test items divided into 19 groups of 12 items. Items increased in difficulty as the test proceeded. Raw and standardized scores were obtained for each child. All children were administered Form A of the PPVT-4. The test took approximately 15 minutes to complete. The PPVT-4 has a mean standard score of 100 and a SD of 15 (Dunn & Dunn, 2007).

Lexically Controlled Words and Sentences

The stimulus lists of lexically controlled words and sentences originally developed by Eisenberg et al. (2002) were used to investigate the effects of word frequency and neighborhood density on word recognition in isolation and in sentences. Eisenberg et al. (2002) created two lists of words based on their lexical properties: one lexically “easy” list and one lexically “hard” list. The authors selected and categorized words as lexically “easy” or “hard” using the methodology described in the Neighborhood Activation Model (Luce, 1986; Luce & Pisoni, 1998) and by Kirk et al. (1995). Lexically “easy” words are high-frequency words with low neighborhood densities (fewer phonetically similar words). Lexically “hard” words are low-frequency words with high neighborhood densities (greater number of phonetically similar words). Each list consisted of 15 practice words and 60 test words produced by one female speaker. The two lists, Easy and Hard, were combined to create one set of 30 practice words and 120 test words that were vocoded and presented in a randomized order. Practice trials always preceded test trials (see Appendix A for a list of words). The vocoded words were played over a high-quality Advent AV570 loudspeaker at 65 dB and were scored for accuracy. For the word recognition task, children were instructed to repeat what they heard. Children did not receive any feedback regarding the accuracy of their responses.

Eisenberg et al. (2002) also created two lists of 25 low-predictability sentences (5 practice and 20 test sentences) using the same easy and hard words that were produced by one female speaker and previously presented in isolation. Each sentence was five to seven words in length and contained three “key” words from either the easy or hard list.

The two sentence lists were combined to create one larger set of 10 practice sentences and 40 test sentences that were also vocoded and presented in a randomized order. Once again, practice trials always preceded the test trials (see Appendix B for a list of sentences). The vocoded sentences were played over the loudspeaker at 65 dB and scored for number of key words correct. For the sentence recognition task, children were instructed to repeat what they heard. Children did not receive any feedback regarding the accuracy of their responses.

Parent Report Measures

Eisenberg Word Familiarity Rating Scale

The Eisenberg Word Familiarity Rating Scale was used to assess each child's familiarity with the test words. Parents were asked to rate their child's familiarity of each of the 150 Eisenberg lexically controlled words on a likert scale ranging from 1 (not at all familiar) to 7 (very familiar).

Part II. Extension to Study 2 of Eisenberg et al. (2002)

Participants

Thirty-one typically-developed monolingual English-speaking young adults (27 females, 4 males) from 18;10 years (years; months) to 25;5 years of age ($M=20;8$ years; $SD=1;7$ years) were recruited for this study. The majority of the sample was Caucasian ($n=30$), with the remaining identified as Asian ($n=1$). By self-report, all adults had normal hearing and vision and no diagnosed cognitive/developmental delays. Adults were college students recruited using IRB approved flyers posted throughout the Psychological and Brain Sciences department at Indiana University. All adults included in data analyses passed a pure-tone hearing screening at 20 dB between 250-4000 Hz to

verify that their hearing was within normal limits.

Performance Measures

Word Intelligibility by Picture Identification- 2nd Edition (WIPI)

The WIPI test is a closed-set spoken word recognition test (Ross, Lerman, & Cienkowski, 2004) that was used to familiarize the participants with vocoded speech. Both children and adults listened to List A, which consisted of 25 vocoded words presented over loudspeaker at 65 dB. The subjects responded by pointing to one of six pictures that matched the word they heard (see Appendix C for example response sheet). Responses were scored for accuracy.

Expressive Vocabulary Test- 2nd Edition (EVT-2)

In addition to the PPVT-4, the EVT-2 was used to obtain a measure of each participant's expressive vocabulary knowledge. This standardized vocabulary assessment can be administered to participants ranging in age from 2;6-90+ years. During administration, the examiner presented the participant with an illustration and read a stimulus question asking the participant to either label the illustration or provide a synonym for a noun, verb, adjective, or adverb. The participant began at a predetermined point based on chronological age and continued until the participant reached ceiling on the assessment. There were a total of 190 items arranged in order of increasing difficulty. Raw and standardized scores were obtained for each participant. All participants were administered Form A of the EVT-2. The test took approximately 15 minutes to complete. The EVT-2 has a mean standard score of 100 and a SD of 15 (Williams, 2007).

Procedures

All participants were tested individually. The study was completed in one test session lasting 1-1.5 hours. Parental and adult consents and child assents, when applicable, were obtained prior to testing as per the guidelines of Indiana University's Institutional Review Board. All assessments, with the exception of the PPVT-4 and EVT-2, were administered in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. At the conclusion of the experiment, all participants received monetary compensation. In addition, all children received two books along with numerous stickers that were distributed throughout the testing session.

Results

Pilot Data and Sentence Gain Scores from Eisenberg et al.'s (2002) Original Dataset and Current Dataset

Results of pilot data collected prior to beginning the replication and extension of Eisenberg et al.'s (2002) study verified that the main findings of the study were reproducible. Eleven typically-developing monolingual English-speaking children (9 females, 2 males) from 5;1 (years; months) years to 12;11 years of age ($M=9;3$, $SD=2;3$) were recruited for the pilot study. Independent samples t -tests were used to assess if the overall pattern of findings was similar to original study. The first analyses assessed whether Easy words were recognized more accurately than Hard words when presented in isolation and in sentences. Recognition of Easy words ($M=27.33$, $SD=13.92$) was significantly better than recognition of Hard words ($M=21.30$, $SD=12.06$) in isolation; $t(10)=3.60$, $p=.005$. The pattern of results was consistent for the sentences. Recognition of Easy sentences ($M=46.27$, $SD=21.50$) was significantly better than recognition of Hard

sentences ($M=39.42$, $SD=18.44$); $t(10)=3.12$, $p=.011$. Analyses of the sentence scores revealed that recognition of words in sentence context was better than words in isolation, a result that was consistent with Eisenberg et al.'s (2002) original findings. Recognition of the words in sentences ($M=42.98$, $SD=19.67$) was significantly better than recognition of words in isolation ($M=24.11$, $SD=12.19$); $t(10)=5.07$, $p<.001$. In summary, the initial pilot study replicated results of Eisenberg et al.'s (2002) original study so a full replication and extension proceeded. The initial pilot data were not included in the full replication or extension of the Eisenberg et al. (2002) study discussed in the proceeding sections.

Before the replication analyses were carried out, a number of additional analyses were conducted using subsets of the original data provided by Dr. Eisenberg. Only 7 of the 12 normal-hearing children from the original Eisenberg et al. study were included in these analyses because of missing data from 5 children. The first set of analyses investigated the effect of sentence context gain in spoken word recognition of vocoded speech. A sentence context gain score was calculated by subtracting percent accuracy scores for words in isolation from percent accuracy scores for the same words in sentences. Because the sentences were scored by key words (i.e. the words presented in isolation that were then embedded in sentences), this score represents the performance gain from having sentence context. Both normal-hearing children from Eisenberg et al.'s (2002) study and the final replication (discussed more in Part II) exhibited the same pattern of results. In each group, the majority of children benefited from the presence of sentence context (see Figures 2.1 and 2.2). However, the group of children with cochlear implants from the original Eisenberg et al. (2002) study displayed a different pattern.

One-third of the children in this group did not show any gain from sentence context (see Figure 2.3). The adults from the final replication (discussed more in Part II) showed the most consistent pattern with all of them benefiting from the additional context provided by sentences (see Figure 2.4). This is a theoretically important finding because it indicates that normal-hearing children and adults routinely make efficient use of sentence context to perceive speech when the acoustic-phonetic information in the signal is degraded. Evidently, children with cochlear implants are less able to use context as efficiently. This pattern is consistent with a recent finding reported by Conway, Walk, Deocampo, Anaya, and Pisoni (in press). They found that normal-hearing children showed gains in performance with the use of context while children with cochlear implants appeared to process meaningful sentences as strings of isolated words showing little or no benefit from sentence context. The ability to bind acoustic-phonetic information with semantic knowledge to aid in recognition also helps to explain why sentence scores are consistently higher than scores for words in isolation.

Part I: Replication of Study 2 of Eisenberg et al. (2002)

Results from averaging the Eisenberg Familiarity Rating Scale data indicated that all children were highly familiar with the test words used ($M=6.91$, $SD=0.16$). Results from the replication analyses support the original findings. As with the data from the original study by Eisenberg et al. (2002), the percent-correct scores were first normalized by subjecting them to an arcsine transformation and then entered into a repeated measure ANOVA to test for main effects of lexical competition (easy and hard) and stimulus type (words and sentences). Analyses revealed that lexically easy words were recognized better than lexically hard words, $F(1,30)=5.82$, $p=.022$ and that words in sentences were

recognized better than words in isolation, $F(1,30)=37.53, p<.001$. The interaction between lexical competition and context was not significant. Figure 2.5 displays the significant difference in performance between easy and hard words in isolation for both Eisenberg et al.'s (2002) original data and child data from the current study. Figure 2.6 displays the significant difference in performance between easy and hard sentences for both Eisenberg et al.'s (2002) original data and child data from the current study. Lastly, Figure 2.7 displays the significant difference in performance between words in isolation and sentences for both Eisenberg et al.'s (2002) original data and child data from the current study. The graphs display raw percent correct scores.

Next, consistent with the analyses completed in the original study, Pearson product-moment correlations were computed between language quotients and the vocoded speech perception measures. The language quotients were derived by taking the PPVT-4 age-equivalency scores and dividing them by the chronological age. This method provided an index of language development that controlled for effects of chronological age. As in the original study, no significant correlations were observed (see Table 2.2).

We also examined the effects of chronological age on speech recognition. Chronological age was found to be significantly correlated with the vocoded sentence perception measures in the original Eisenberg et al. (2002) study and this pattern was also found with all of the vocoded speech perception measures in the current study (see Table 2.3). Chronological age was significantly correlated with performance on words in isolation ($r=.59, p<.001$), lexically easy words in isolation ($r=.65, p<.001$), and lexically hard words in isolation ($r=.49, p=.006$). Chronological age was also significantly

correlated with performance on sentences ($r=.73, p<.001$), lexically easy sentences ($r=.68, p<.001$), and lexically hard sentences ($r=.73, p<.001$).

Part II. Extension to Study 2 of Eisenberg et al. (2002)

The first part of the extension was the addition of the WIPI to the performance measures for the children and adults. The WIPI was administered prior to the first vocoded speech perception task in order to familiarize the child or adult with vocoded speech. Since this was a familiarization task, no formal analyses of the scores were conducted, but it is important to note here that all participants were able to perform at or above chance on this test with the exception of one child (see Figures 2.8 and 2.9).

Second, the EVT-2 was included to obtain a converging measure of the role of vocabulary knowledge on vocoded speech perception. Pearson product-moment correlations were computed between the language quotient derived using the EVT-2 and the vocoded speech perception measures. The language quotients were derived by taking the EVT-2 age-equivalency scores and dividing them by the chronological age. One significant correlation was uncovered between the EVT-2 language quotient and easy sentences (see Table 2.4), which suggest that expressive vocabulary may be an important index of the use of context in vocoded sentences and that expressive vocabulary measured with the EVT-2 may be a stronger predictor of performance than receptive vocabulary assessed by the PPVT-4.

Finally, a group of young adults were included to provide a baseline measure of performance that eliminated influences of age or development. As with the previous analyses, the percent-correct scores were normalized by subjecting them to an arcsine transformation and then entered into a repeated measure ANOVA testing for main effects

of lexical density (easy and hard) and stimulus type (words and sentences). Analyses revealed that lexically easy words were recognized more accurately than lexically hard words, $F(1,30)=38.83, p<.001$ and words in sentences were recognized better than words in isolation, $F(1,30)=95.62, p<.001$. The interaction between lexical competition and context was also significant, $F(1,90)=6.37, p=.013$ with hard words being more difficult in isolation than in sentences (see Figures 2.10-2.12 for raw percentage score figures).

Discussion

The purpose of this study was to replicate the findings from Experiment 2 of Eisenberg et al. (2002) using a larger sample of children and to compare their performance on the vocoded speech tasks with adults. We were able to successfully replicate the main findings from the Eisenberg et al. (2002) study by showing that lexically easy words were recognized better than lexically hard words in both isolation and in sentences and that accuracy for words in sentences was better than for the same words presented in isolation. These findings were also consistent with predictions made by the NAM model of spoken word recognition (Luce & Pisoni, 1998). Replicating Eisenberg et al.'s (2002) original study, we found that language abilities, as measured by the PPVT-4 language quotient, were not significantly related to vocoded speech perception measures, however chronological age was highly significant with older children performing better than younger children on all vocoded speech perception measures.

While the main findings were replicated, one difference was observed between the original dataset from Eisenberg et al. (2002) and the present results. The overall mean performance scores for the children from Eisenberg et al.'s (2002) original study

were higher than the overall mean performance for the present dataset. One explanation for the differences in the two studies could be that more than half of Eisenberg et al.'s (2002) participants (7 of 12) were used in their previous Experiment 1, which could have made them more familiar with the stimuli in Experiment 2. Prior experience with these stimuli would have created an advantage for recognizing the speech stimuli under spectral degradation (Bent, Buchwald, & Pisoni, 2009; Davis, Johnsrude, Hervais-Adelman, Taylor, & McGettigan, 2005). Another possibility could be that the small N in Eisenberg et al.'s (2002) original study was not representative of the ages included and when more children were recruited, the average scores decreased.

While the original set of findings was replicated with the adults, their average scores were much higher than both Eisenberg et al.'s (2002) and the current study's groups of children. The significant correlations between age and vocoded speech perception measures suggest that more mature language systems and greater vocabulary knowledge are important for recognition of vocoded speech. We also found a smaller difference between the easy and hard words for the adults in the sentence condition and a significant interaction between lexical competition and context. The smaller difference between easy and hard words could be due to the fact that the stimuli used were chosen from a child's lexicon and with the benefit of context, the effects of lexical familiarity and neighborhood density was attenuated. The interaction means that the additional context provided by sentences significantly aided in the recognition of hard words, suggesting that adults are effectively able to utilize context when less than ideal listening conditions are present. The adults, unlike the children, did not show any significant correlations between performance on vocoded speech and vocabulary level or age. It is

likely that this was a result of a more restricted age range with many adults having very similar vocabulary levels. Moreover, because adults are more cognitively mature, the effects of age and vocabulary knowledge were not expected to be important of factors underlying performance on these tasks.

One potential issue with this study, although it is outside the scope of the original study, was whether any perceptual learning of vocoded speech took place. Although the participants did not receive any feedback during the experiment and completed the WIPI as a familiarization task in addition to the practice words and sentences before each condition, rapid perceptual learning of degraded speech has been shown to take place over a short period of time even when participants are only passively exposed to vocoded speech. For example, Davis, Johnsrude, Herbais-Adelman, Taylor and McGettigan (2005) investigated the processes involved in perceptual learning of six-channel noise-vocoded speech in college-aged normal-hearing adults. They carried out a series of experiments to determine if passive perceptual learning occurs through exposure alone and compared this condition to the effects resulting from different types of context and training. Most relevant to the current research are the results from their Experiment 1, which investigated passive perceptual learning. Davis and colleagues (2005) found an improvement in performance on vocoded sentence materials when participants were only exposed to 30 sentences, revealing rapid improvement in speech recognition performance in a short period of time with no explicit feedback or training.

With these results in mind, perceptual learning effects of vocoded speech were also investigated in the current study. First, we investigated whether or not perceptual learning occurred during the vocoded words in isolation task. Because the order of

presentation for vocoded speech materials was counterbalanced, the groups of participants could be divided into two groups depending on whether they received the words first (Children, $n=16$; Adults, $n=16$) or the words second (Children, $n=15$; Adults, $n=15$). Next, the words were divided into 4 blocks of 30 words. Block 1 represented the first 30 words each participant heard, Block 2 the second set of 30 words, and so on. The total number of words correctly recognized was summed over the participants for each block and is displayed in Figure 2.13.

Two sets of analyses were then carried out to investigate the effects of perceptual learning: within-task and between-groups. To assess if any perceptual learning occurred when the vocoded words were presented in isolation, one-sample t -tests were computed between presentation blocks for both groups. Analyses revealed no significant difference in performance between presentation blocks for either group suggesting that no perceptual learning took place during the isolated word task. However, evidence of perceptual learning was found when we examined the difference in performance between the two counterbalanced groups (the group that received words first compared to the group that received words second). A one-way ANOVA revealed that the group that received the words in isolation second (after the words in sentences) did significantly better on Block 1 [$F(1,29)=7.28, p=.011$], Block 3 [$F(1,29)=5.63, p=.025$], and Block 4 [$F(1,29)=14.18, p<.001$] (see Figure 2.13). This suggests that the group that received the words in isolation second benefited from the previous exposure to the vocoded words in sentences.

A similar pattern of performance was found in an analysis of the data from the adult group. A series of one-sample t -tests computed between presentation blocks for

both groups of adults revealed only one significant difference in performance. The adult group that received the words second displayed significantly better performance on Block 1 ($M=13.33$, $SD=2.9$) than on Block 4 ($M=11.6$, $SD=2.9$); $t(14)=2.73$, $p=.016$. This pattern suggests that the adult group actually got worse in performance during the task. One explanation for the decrease in performance could be that the adults may have started to experience cognitive fatigue resulting in less effort extended to the task at the end. This may have also happened in the group of children, but because their performance was lower overall, it may not have been as observable in their performance. As with the group of children, evidence of perceptual learning was found when we examined the difference in performance between the two groups of adults. A one-way ANOVA revealed that the adult group that received the words in isolation second did significantly better on Block 1 [$F(1,29)=13.55$, $p<.001$], Block 2 [$F(1,29)=13.23$, $p<.001$], Block 3 [$F(1,29)=8.18$, $p=.008$], and Block 4 [$F(1,29)=4.57$, $p=.041$] than the group that received words in isolation first.

Next, perceptual learning during the vocoded sentences condition was examined. Because the order of presentation for vocoded speech materials was also counterbalanced, the groups of participants could again be divided into two groups depending on whether they received the words first (Children, $n=16$; Adults, $n=16$) or the words second (Children, $n=15$; Adults, $n=15$). To do this analysis, the sentences were divided into 4 blocks of 10 sentences each. Block 1 represented the first 10 sentences each participant heard, Block 2 the second set of 10 sentences, and so on. The total number of sentences correctly recognized was then summed over the participants for each block and the results are displayed in Figure 2.14. Two sets of analyses were then carried out to

investigate the effects of perceptual learning: within-task and between-groups. To determine if perceptual learning occurred with vocoded words in sentences, one-sample *t*-tests were computed between blocks for both groups. Analyses revealed three significant differences in performance between blocks for the children that received the sentences first. First, a significant difference was found between Block 1 ($M=9.93$, $SD=7.06$) and Block 2 ($M=13.0$, $SD=7.75$); $t(14)=3.304$, $p=.005$. Second, a significant difference was found between Block 1 ($M=9.93$, $SD=7.06$) and Block 3 ($M=13.87$, $SD=8.5$); $t(14)=3.58$, $p=.003$. Third, a significant difference was found between Block 1 ($M=9.93$, $SD=7.06$) and Block 4 ($M=14.33$, $SD=6.87$); $t(14)=3.58$, $p=.003$. No significant differences were found in the group of children receiving sentences second or in either of the adult groups. Unlike the vocoded words in isolation condition, one-way ANOVAs revealed no evidence of any perceptual learning with sentences when we examined the difference in performance between groups in children and adults.

In summary, the investigation of perceptual learning revealed that with increased exposure to vocoded speech, both children and adults improved in recognizing vocoded words in isolation, as seen with difference in performance between groups that heard words first compared to groups that heard the words second, but generally did not improve or learn within the task itself. No significant improvement was observed for either group in the sentence condition, except for the group of children that received the sentences first, where learning appeared to take place within the task.

Conclusions

Investigating vocoded speech perception in normal-hearing children is an important step in understanding the effects of degraded auditory input on speech

perception in cochlear implant users. Successfully replicating the Eisenberg et al. (2002) study has several important theoretical implications. First, the replication provides supporting evidence for the importance of lexical density and word frequency on vocoded speech recognition. Second, replicating the original study is a critical prerequisite for the new research studies reported below that made use of Eisenberg et al.'s (2002) original stimuli and methodology. Having successfully replicated the original study now allows for future research using the methodology to investigate the relations between vocoded speech and cognitive processes, a suggestion made by Eisenberg et al. (2002) in their original paper.

The extension of the replication provided additional insight into vocoded speech perception in these two groups of listeners. First, by examining sentence gain scores a clearer picture emerged regarding how sentences are perceived better by normal-hearing listeners and that children with cochlear implants are doing poorly when words are in sentence context. This suggests that children with cochlear implants are unable to use context efficiently to aid them in spoken word recognition. Second, expressive vocabulary scores showed a stronger relationship to vocoded speech perception compared to receptive vocabulary scores. During the expressive vocabulary assessment, children have to generate the correct word from memory when provided with a short prompt and a visual cue. Generating the correct word from memory requires that the words, including their linguistic characteristics and semantic associations, have been encoded with robust memory traces and are available for recall. The receptive vocabulary assessment is administered in a closed set four-alternative forced-choice format where children are provided with four visual cues. This format promotes guessing where the child has a

25% chance of getting the answer correct without having to know the definition of the word. The expressive vocabulary test may be more representative of the child's language abilities because of the increased difficulty of the task, which resulted in stronger correlations with performance on the vocoded sentence recognition task. Third, adults displayed the same pattern as children when words were presented in isolation but were affected less by lexical density and word frequency when words were embedded in sentences. Finally, perceptual learning of degraded vocoded speech appears to take place in normal-hearing children and adults in a relatively short period of time suggesting that rapid adaptation and adjustment are fundamental skills that promote robust speech recognition in challenging listening conditions.

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Table 2.1. Frequency Bandwidths for the 4-Channel Vcoded Simulation

Spectral Channel	Lower Frequency Cutoff (Hz)	Higher Frequency Cutoff (Hz)	Channel Bandwidth (Hz)
1	300	722	422
2	722	1528	806
3	1528	3066	1538
4	3066	6000	2934

Table 2.2. Pearson Correlational Analyses Between PPVT-4 Language Quotient and Vcoded Speech Perception Scores for Children

Speech Perception Measures	Eisenberg Data ¹ (N=12) Language Quotient	Replication Data (N=31) Language Quotient
Words in Isolation	.36	.07
Easy Words	.29	.08
Hard Words	.38	.06
Sentences (Keywords)	.14	.25
Easy Sentences	-.03	.29
Hard Sentences	.26	.20

Note. Speech perception measures reflected percent accuracy.

¹The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Table 2.3. Pearson Correlational Analyses Between Chronological Age and Vcoded Speech Perception Scores for Children

Speech Perception Measures	Eisenberg Data ¹ (N=12) Chronological Age	Replication Data (N=31) Chronological Age
Words in Isolation	.26	.59***
Easy Words	.07	.65***
Hard Words	.39	.49**
Sentences (Keywords)	.80**	.73***
Easy Sentences	.65*	.68***
Hard Sentences	.84***	.73***

Note. Speech perception measures reflected percent accuracy.

¹The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Table 2.4. Pearson Correlational Analyses Between EVT-2 Language Quotient and Vcoded Speech Perception Scores for Children

Speech Perception Measures	Replication Data ($N=31$) EVT-2 Language Quotient
Words in Isolation	.27
Easy Words	.28
Hard Words	.25
Sentences (Keywords)	.34
Easy Sentences	.41*
Hard Sentences	.15

Note. Speech perception measures reflected percent accuracy.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Figure Captions

Figure 2.1. Sentence gain scores for NH children in the Eisenberg et al. (2002) original data set ($N=12$). The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California. Sentence gain scores were derived by subtracting performance scores on lexically controlled words in isolation from performance scores on lexically controlled sentences. Each bar represents an individual child's sentence gain score. Gain scores are ordered from lowest to highest.

Figure 2.2. Sentence gain scores for NH children in the replication data set ($N=31$). Sentence gain scores were derived by subtracting performance scores on lexically controlled words in isolation from performance scores on lexically controlled sentences. Each bar represents an individual child's sentence gain score. Gain scores are ordered from lowest to highest.

Figure 2.3. Sentence gain scores for the children with CIs in the Eisenberg et al. (2002) original data set ($N=12$). The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California. Sentence gain scores were derived by subtracting performance scores on lexically controlled words in isolation from performance scores on lexically controlled sentences. Each bar represents an individual child's sentence gain score. Gain scores are ordered from lowest to highest.

Figure 2.4. Sentence gain scores for NH adults in the replication data set ($N=31$). Sentence gain scores were derived by subtracting performance scores on lexically controlled words in isolation from performance scores on lexically controlled sentences.

Each bar represents an individual adult's sentence gain score. Gain scores are ordered from lowest to highest.

Figure 2.5. Mean scores for lexically easy and hard words in isolation. Both the children from Eisenberg et al.'s (2002) study ($N=12$) and the replication data set ($N=31$) showed better performance for easy words in comparison to hard words when presented in isolation. The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California. Error bars represent standard error.

Figure 2.6. Mean scores for lexically easy and hard words in sentences. Both the children from Eisenberg et al.'s (2002) study ($N=12$) and replication data set ($N=31$) showed better performance for easy words in comparison to hard words when presented in sentences. The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California. Error bars represent standard error.

Figure 2.7. Mean scores for lexically controlled words and sentences. Both the children from Eisenberg et al.'s (2002) study ($N=12$) and the replication data set ($N=31$) showed poorer performance for words presented in isolation than for the same words presented in sentences. The original data set from the Eisenberg et al. (2002) was directly obtained from Dr. Eisenberg at the University of Southern California. Error bars represent standard error.

Figure 2.8. WIPI scores (percent accuracy) for the NH children in the replication data set ($N=31$) plotted against age. Each bar or point represents an individual child's WIPI score.

The red line marks performance at chance levels. The blue line marks mean performance of the children.

Figure 2.9. WIPI scores (percent accuracy) for the NH adults in the replication data set ($N=31$) plotted against age. Each bar or point represents an individual adult's WIPI score. The red line marks performance at chance levels. The blue line marks mean performance of the adults.

Figure 2.10. Mean scores for lexically easy and hard words in isolation. The adults in the replication data set ($N=31$) showed better performance for easy words in comparison to hard words when presented in isolation. Error bars represent standard error.

Figure 2.11. Mean scores for lexically easy and hard words in sentences. The adults in the replication data set ($N=31$) did not show a significant difference in performance for easy words in comparison to hard words when presented in sentences. Error bars represent standard error.

Figure 2.12. Mean scores for lexically controlled words and sentences. The adults in the replication data set ($N=31$) showed poorer performance for words presented in isolation than for the same words presented in sentences. Error bars represent standard error.

Figure 2.13. Effects of perceptual learning in NH children and adults for vocoded words in isolation. Both children and adults were divided into two separate groups depending on whether they completed the vocoded words in isolation first or second (vocoded sentences were presented first). The y-axis displays the sum of the number of accurate words correctly recognized in each block. Words were grouped into 4 blocks of 30 words with Block 1 containing the first 30 words presented, Block 2 the second group of 30 words, Block 3 the third group of 30 words, and Block 4 the last group of 30 words.

Figure 2.14. Effects of perceptual learning in NH children and adults for vocoded sentences. Both children and adults were divided into two separate groups depending on whether they completed the sentences first or second (vocoded words in isolation were presented first). The y-axis displays the sum of the number of accurate words correctly recognized in each block of sentences. Sentences were grouped into 4 blocks of 10 sentences with Block 1 containing the first 10 sentences presented, Block 2 the second group of 10 sentences, Block 3 the third group of 10 sentences, and Block 4 the last group of 10 sentences.

Figure 2.1.

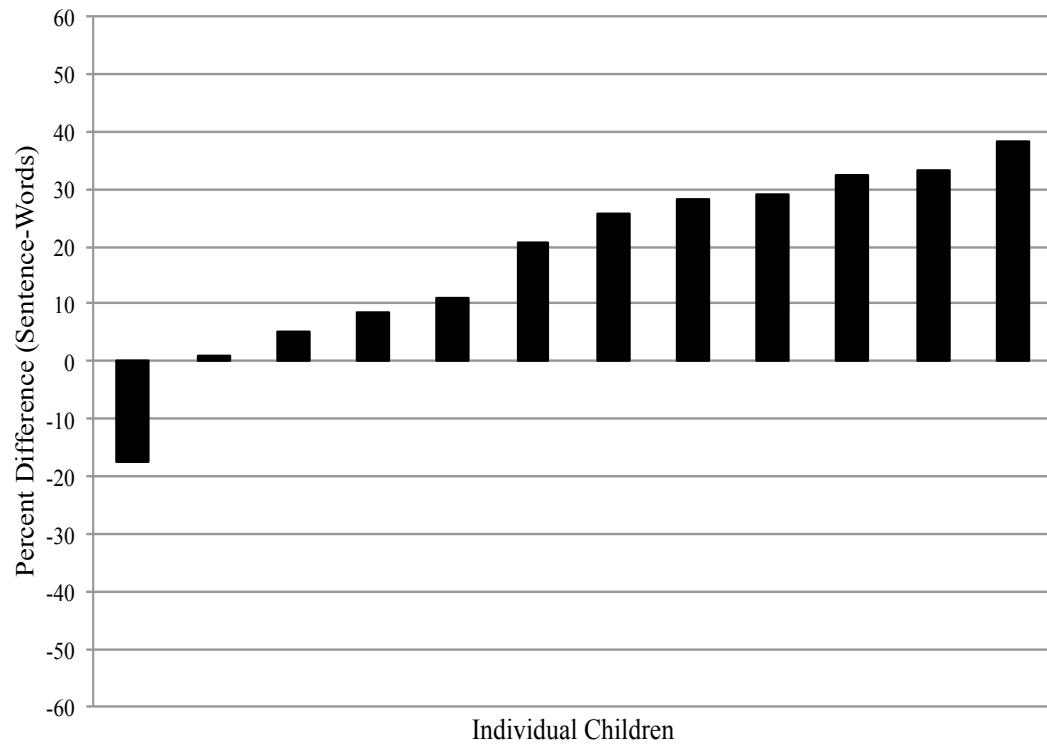


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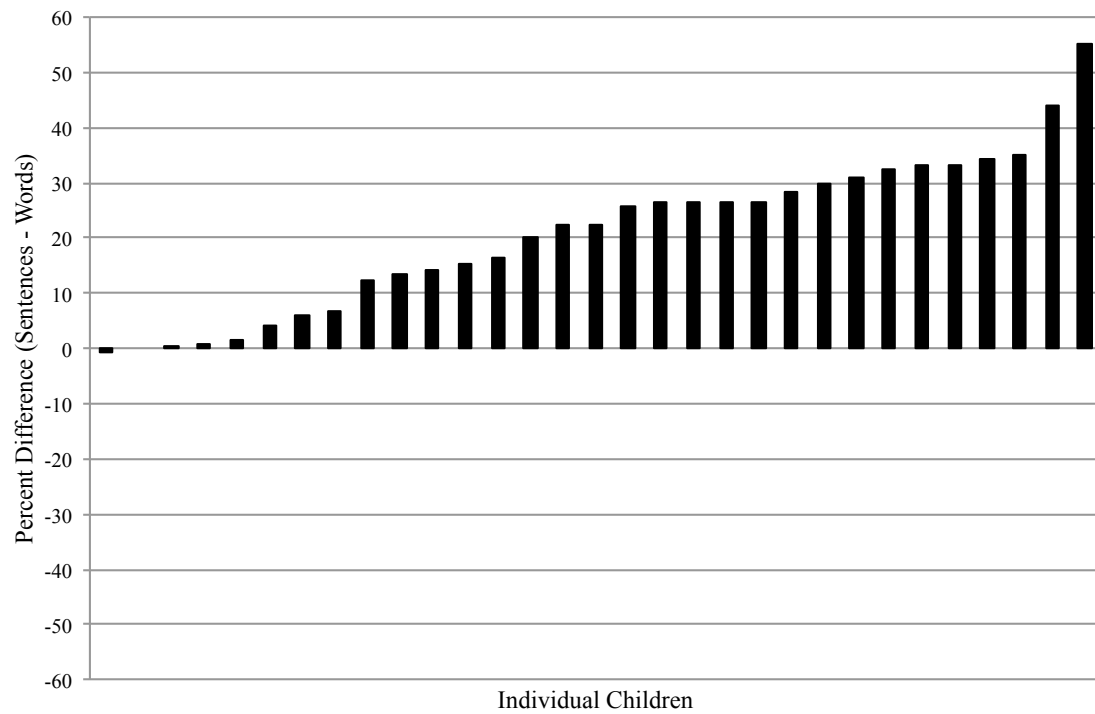


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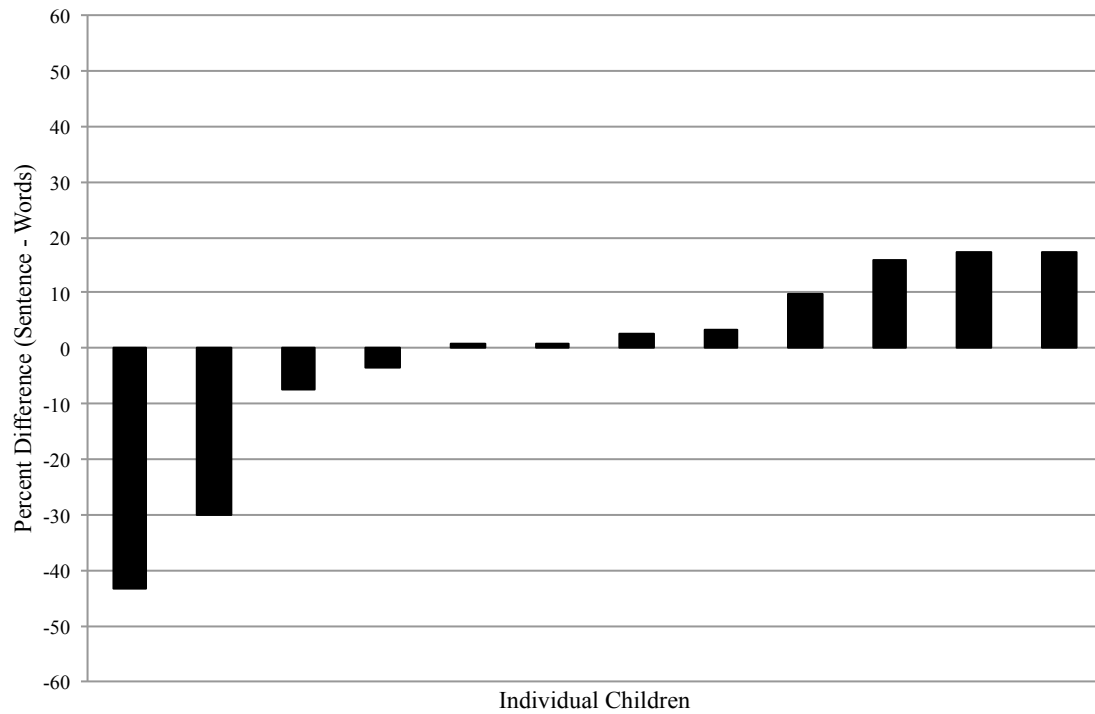


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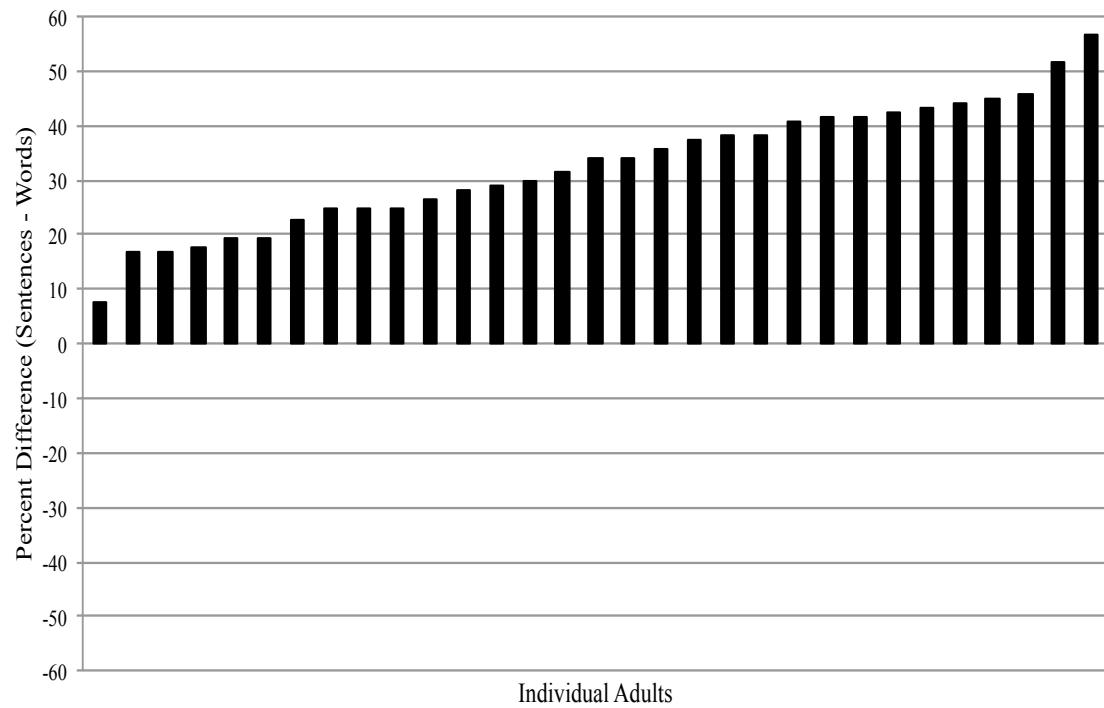


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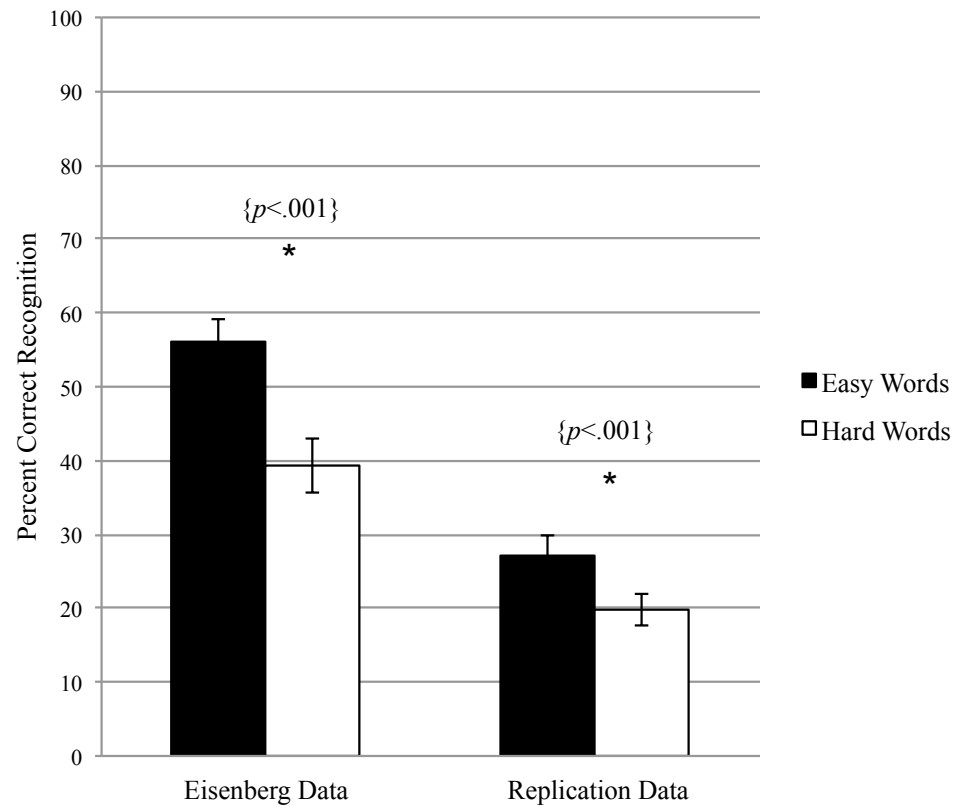


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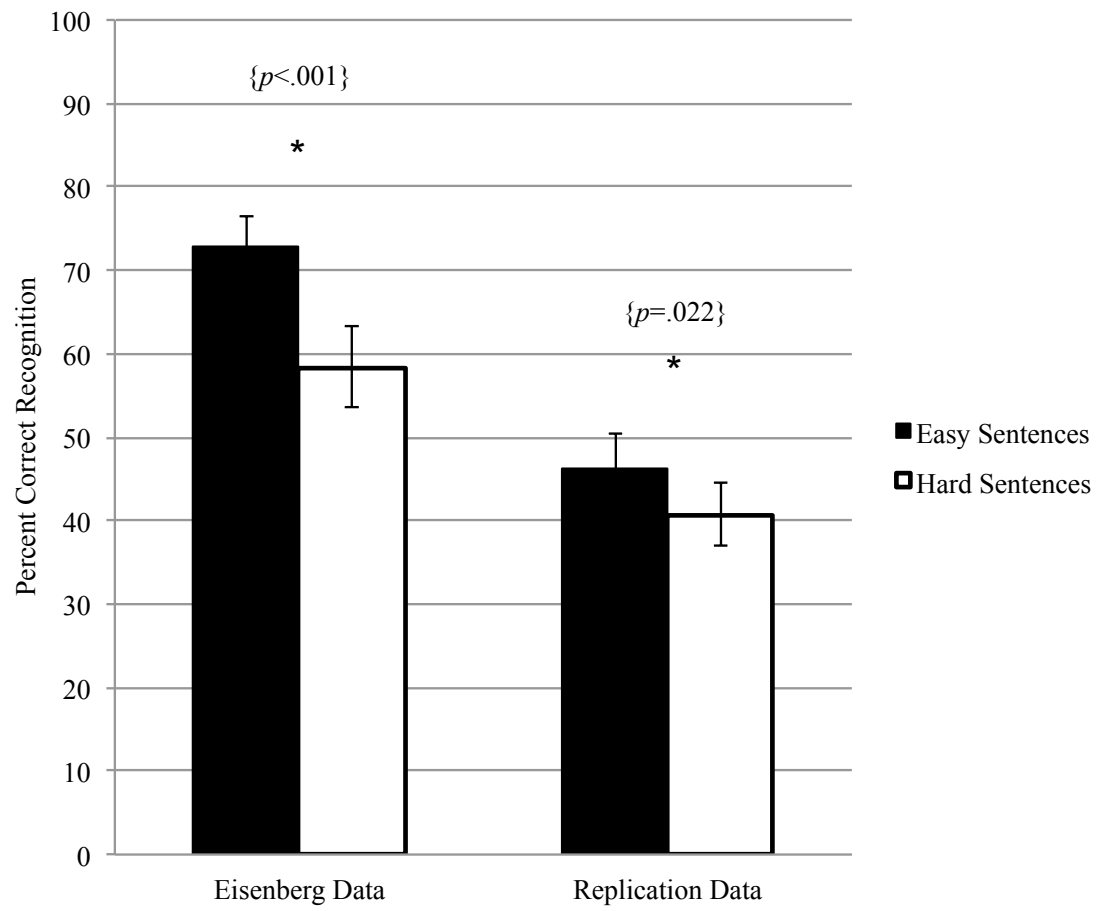


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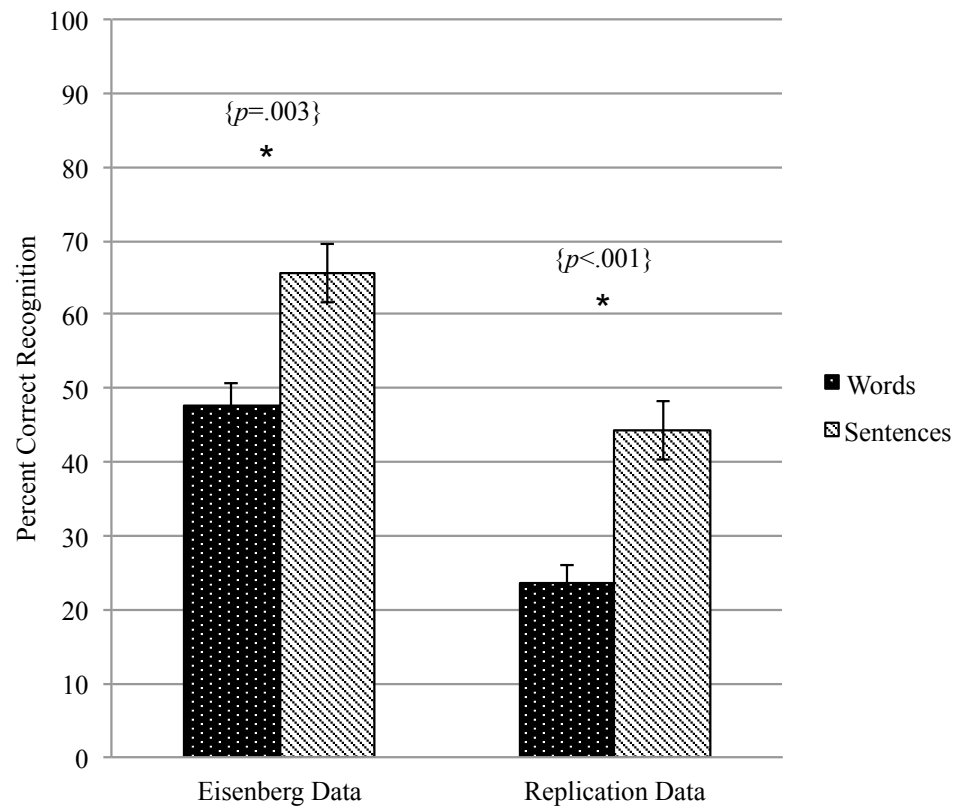


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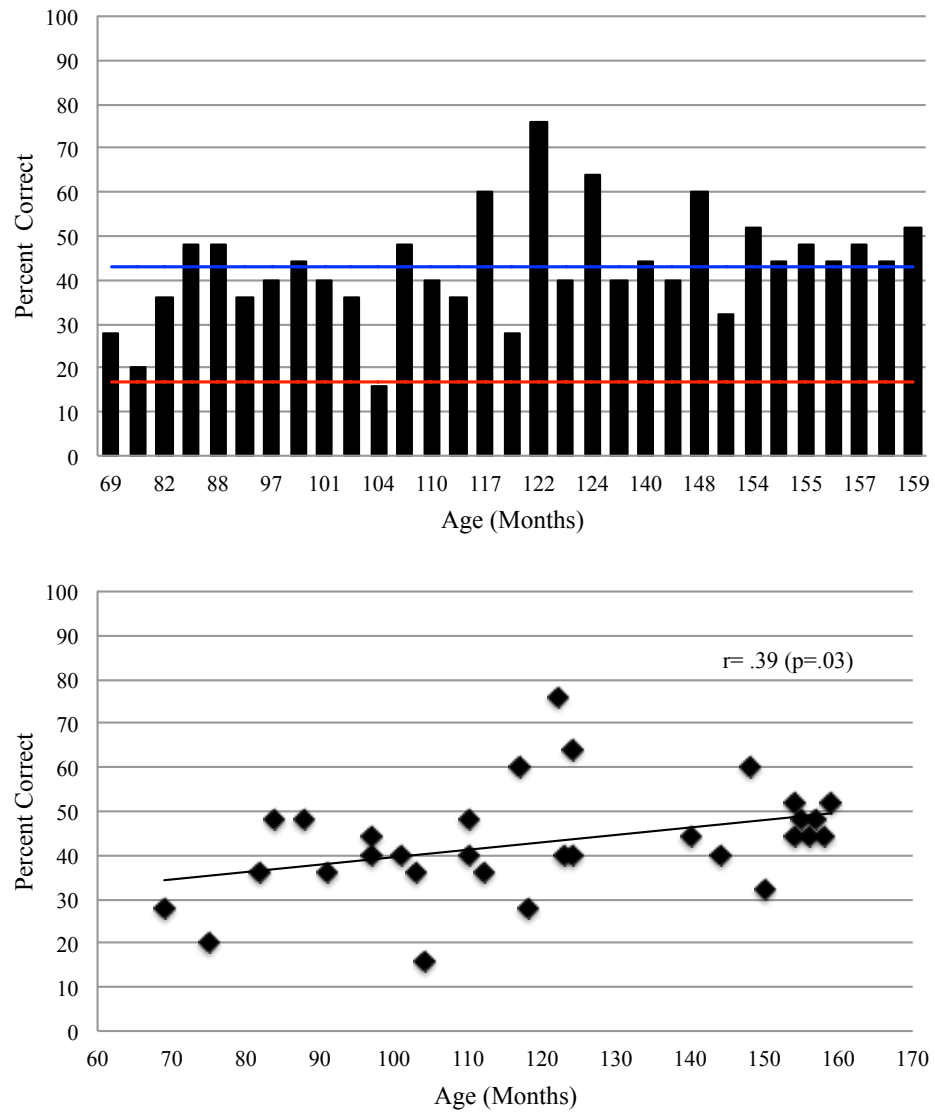


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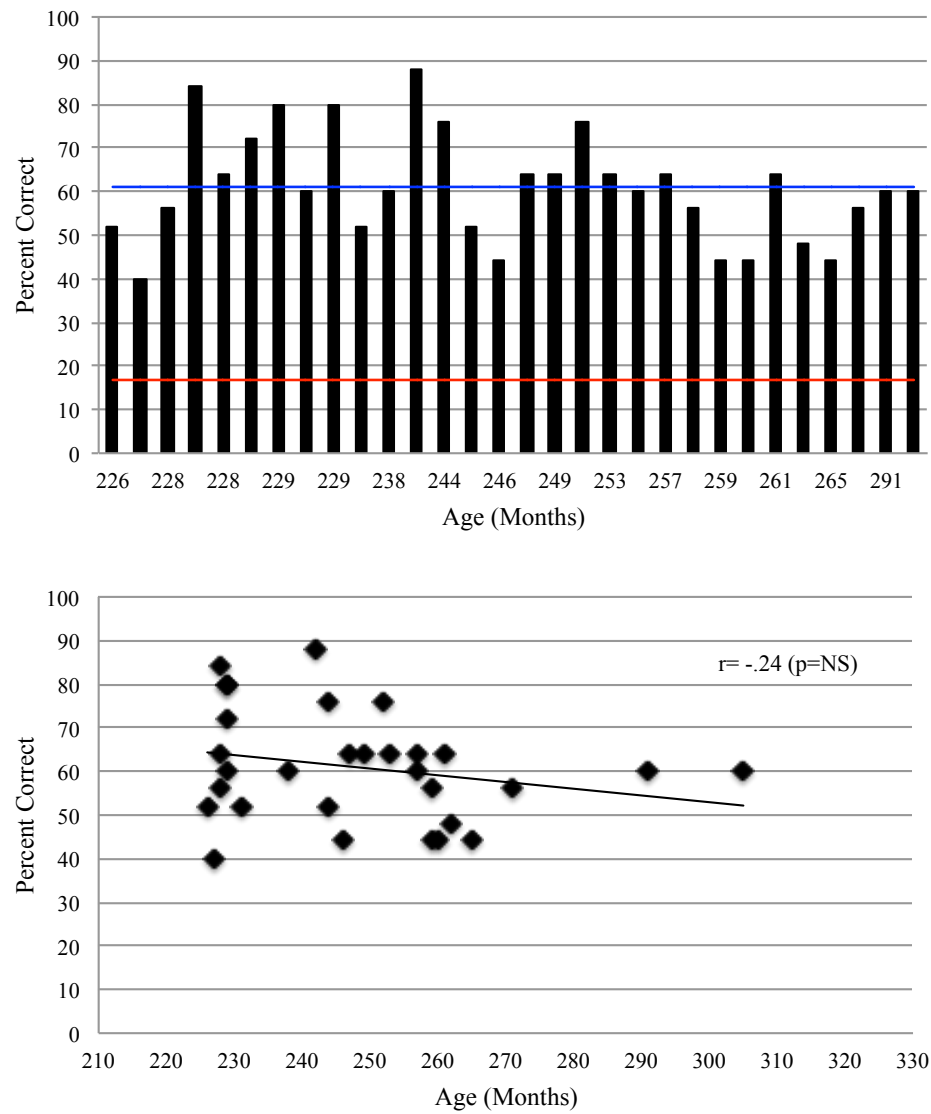


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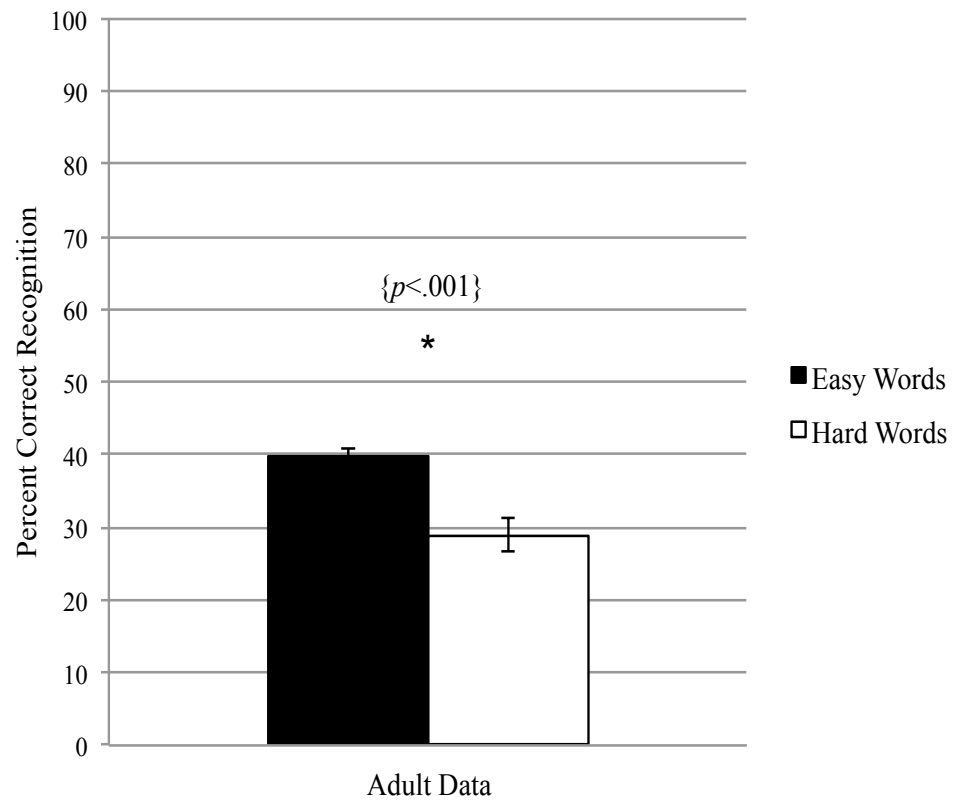


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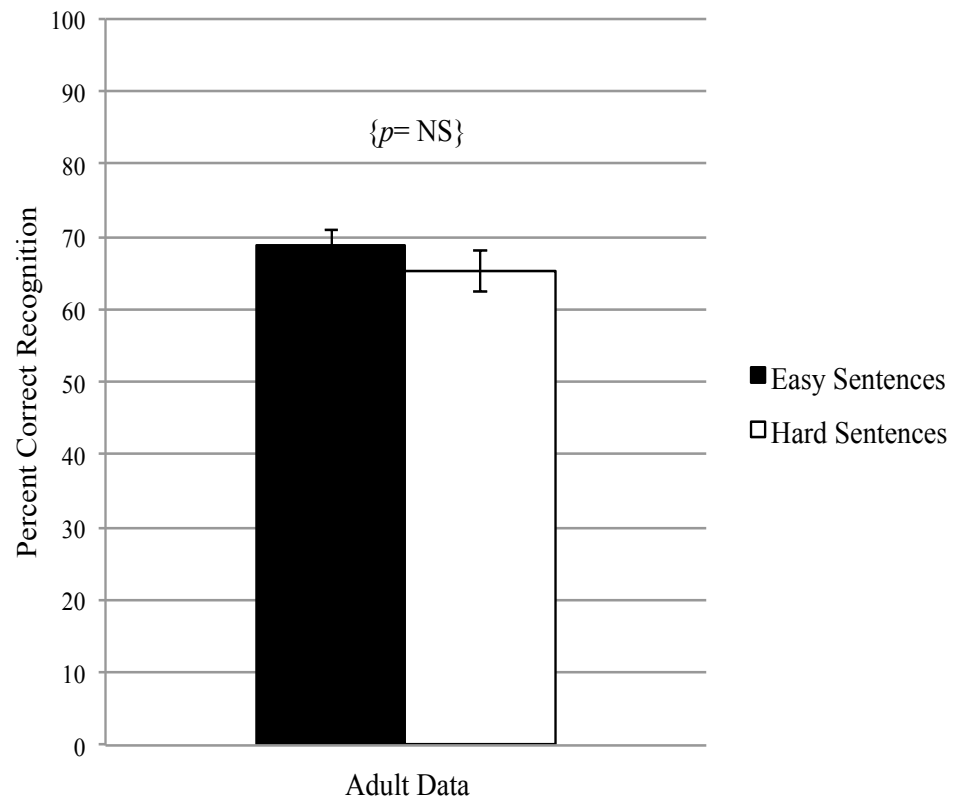


Figure 2.12

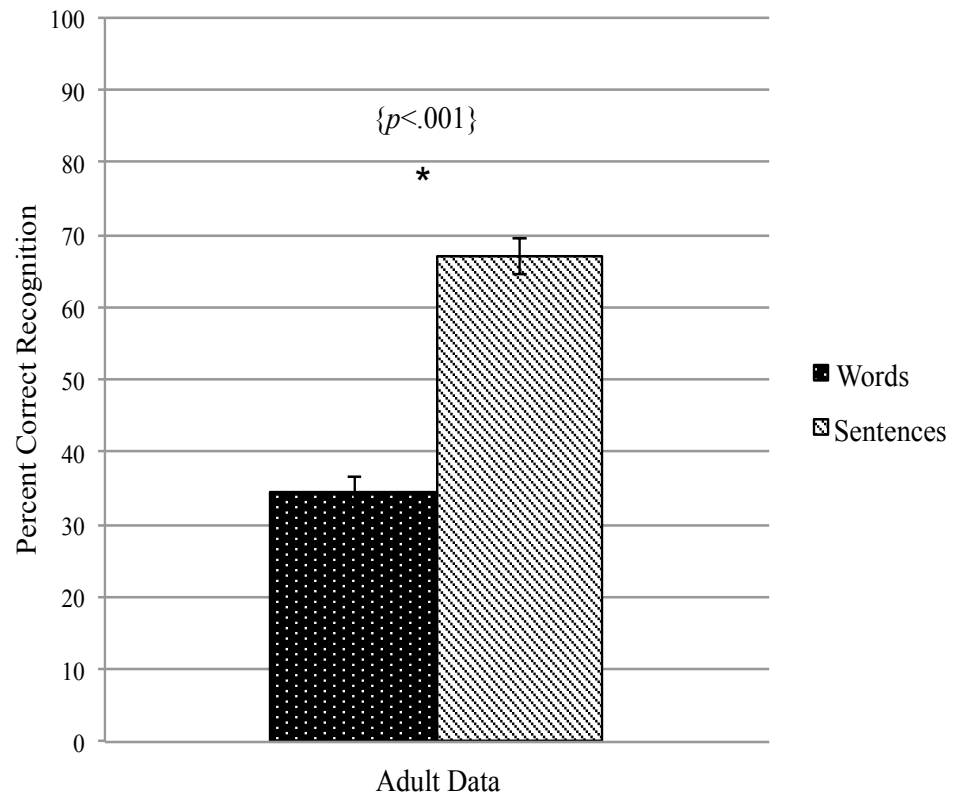


Figure 2.13

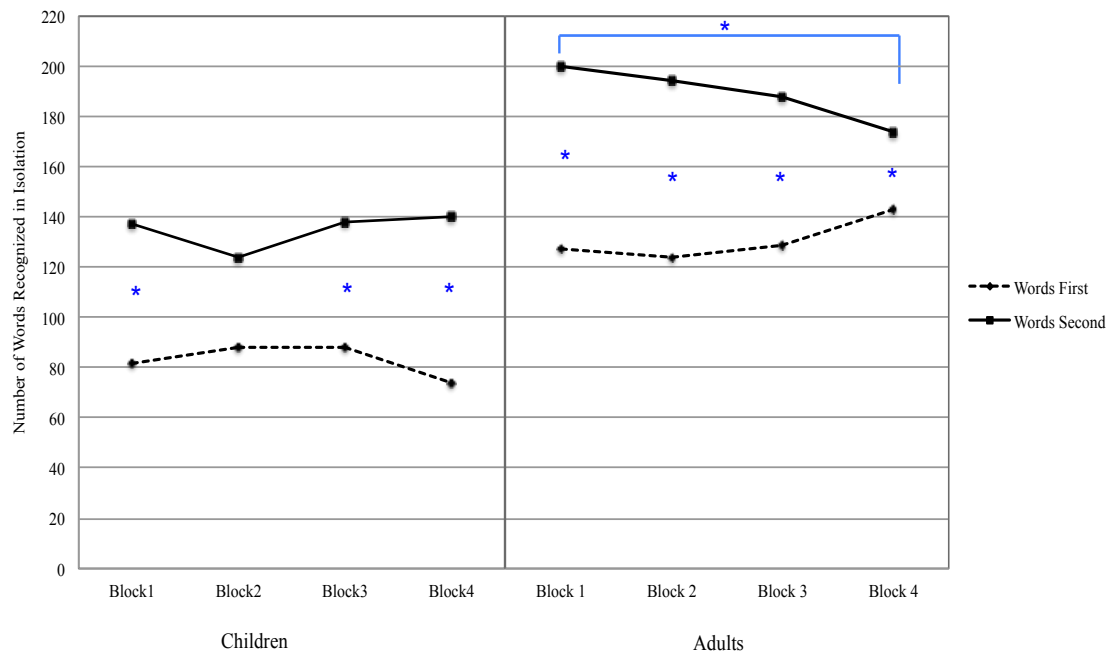
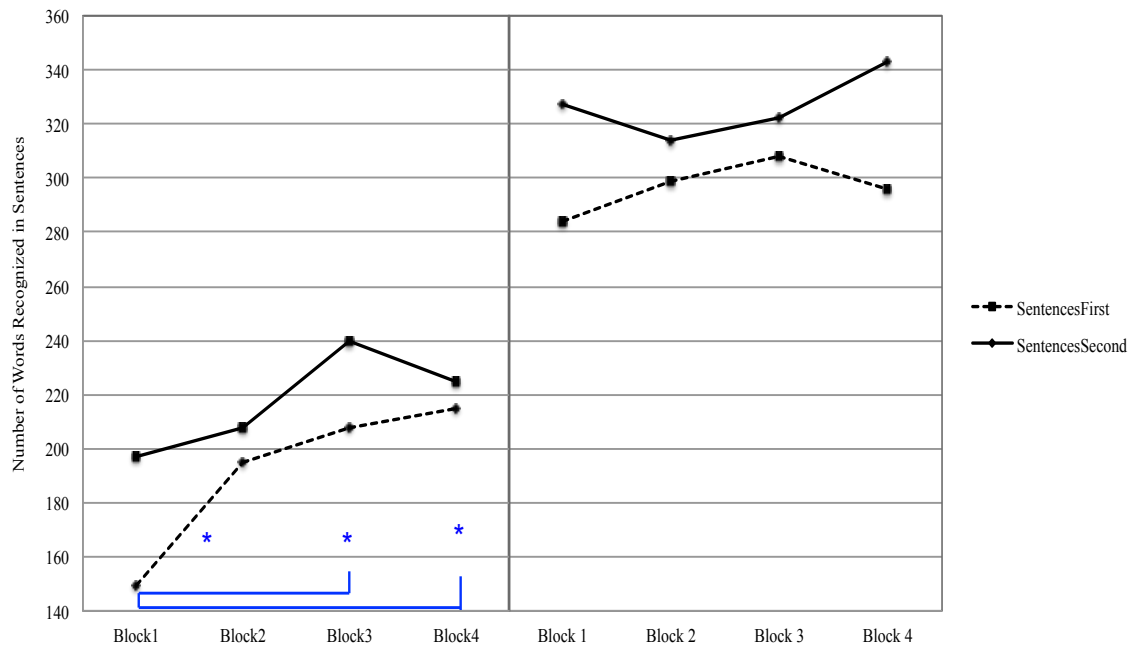


Figure 2.14



CHAPTER 3

NEUROCOGNITIVE CORRELATES OF VOCODED SPEECH PERCEPTION IN CHILDREN

Introduction

Researchers have learned a great deal about speech perception and cognition by studying individuals with hearing impairment, especially individuals who are born deaf and later receive cochlear implants (CIs) as a medical intervention in profound sensory-neural hearing loss (Niparko, 2009; Waltzman & Roland, 2006; Zeng, Popper, & Fay, 2004). While the use of hearing aids and CIs has provided immeasurable benefit to individuals with hearing impairments, especially children who are born with severe-to-profound hearing loss, a period of early auditory deprivation can be detrimental to cognitive development (Niparko, 2009; Nitttrouer, 2010). Because the brain is remarkably plastic, auditory deprivation and compromised acoustic input, especially during the critical periods for language development, can result in brain restructuring and reorganization from lack of normal sensory input (Gilley, Sharma, & Dorman, 2008).

Auditory deprivation and language delays have been shown to negatively impact cognitive development and functioning in children with CIs. For example, children with CIs have significant delays and deficits in working memory (Burkholder & Pisoni, 2003; Pisoni, Kronenberger, Roman, & Geers, 2011), verbal short-term memory (Harris et al., 2013), language and reading (Johnson & Goswami, 2010), implicit sequence learning (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011), visual attention (Horn, Davis, Pisoni, & Miyamoto, 2005; Quittner, Smith, Osberger, Mitchell, & Katz, 1994) and theory-of-mind (Peterson, 2004).

Studying cognition in children who receive CIs is often complicated because of the involvement of additional demographic factors related to hearing loss (e.g. age at onset of hearing loss, age of implantation, and etiology of hearing loss). Using spectrally-degraded vocoded speech has been a valuable research tool because it allows researchers to test hypotheses about the effects of degraded speech input on typically-developing cognitive systems and also how neurocognitive functioning affects speech perception (Conway, Walk, Deocampo, Anaya, & Pisoni, in press; Dorman, Loizou, Kemp, & Kirk, 2000; Eisenberg, Martinez, Holowecky, & Pogorelsky, 2002; Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Maidment, Kang, Stewart, & Amitay, 2014; Newman & Chatterjee, 2013; van Heugten, Volkova, Trehub, & Schellenberg, 2013; Vongpaisal, Trehub, Schellenberg, & van Lieshout, 2012; Warner-Czyz, Houston, & Hynan, 2014). Vocoded speech refers to speech signals that have been processed to preserve gross temporal and amplitude information but have degraded fine spectral information in the signal (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). This type of signal processing strategy was created by Shannon et al. (1995) to model the way a CI processes speech. Unfortunately, very little research has used vocoded speech with normal-hearing (NH) children and the existing literature has primarily focused on the early sensory aspects of speech perception. It is important to investigate the effects of neurocognitive functioning on the perception of degraded speech because previous research has shown that recognition of degraded speech is not just related to the amount of information available in the speech signal (Eisenberg et al., 2002; van Heugten et al., 2013) but that cognitive abilities account for some variability in performance. The purpose of the research reported here was to use vocoded speech in NH children to assess

relations between vocoded speech perception abilities and several aspects of cognition. More specifically, we investigated relations between vocoded sentence perception and measures of auditory attention and short-term memory.

Attention, as it pertains to this research, refers to the properties of cognition involving control and allocation of limited processing resources and capacities (*controlled* attention, as opposed to attention as a basic perceptual process (Cowan, 1995)). Attention has limited processing resources and capacity that operate to keep information active in working memory during different cognitive processes. Auditory attention specifically refers to keeping information active in memory that has been presented auditorally to the listener. Although auditory attention capabilities are critical to speech perception and the development of spoken language, almost all of the research on attention in children with CIs has focused on visual attention (Horn et al., 2005; Quittner et al., 1994; Smith, Quittner, Osberger, & Miyamoto, 1998; Tharpe, Ashmead, & Rothpletz, 2002). The existing literature on auditory attention in CI children has been concerned with the child's ability to attend to a stream of speech in the presence of noise or other distractors such as dichotic listening tasks. Although this research is important because of its ecological validity and relevance to listening to speech in the real world, outside the laboratory or clinic, the presence of noise or competing distracting tasks creates an additional cognitive load. As a result, greater effort is required to inhibit competition from irrelevant information while the listener focuses and directs attention to the target information. Additional research is needed to better understand the role of basic attentional processes in speech perception, especially when the acoustic input is highly degraded via a CI or a simulation of a CI using vocoded speech since very little is

known about the relationship between auditory attention and speech perception at this time.

One approach to studying the relations between auditory attention and speech perception has been to use a talker discrimination task. Cleary and Pisoni (2002) first developed and used this measure with young CI and NH children. The talker discrimination task is unique because it requires the listener to attend to the indexical properties of speech and inhibit processing of the linguistic content. Indexical properties of speech provide personal information about the talker such as gender, dialect, and emotional or physical states. Linguistic properties of speech refer to the phonological and lexical content of the talker's intended utterance. Identifying or discriminating between talkers requires the listener to be able to perceive and encode the indexical properties of speech that are specific to each speaker. This task has been found to be quite difficult for CI users because of the reduced spectral detail in the speech signal processed by the CI. In order to successfully complete the talker discrimination task, a listener has to ignore and inhibit attention to the linguistic content of the sentence and focus attention instead on the indexical characteristics.

The children in the original Cleary and Pisoni (2002) talker discrimination study were asked to listen to pairs of sentences and then decide if the sentences in each pair were spoken by the same talker or two different talkers. Their study examined two conditions: a fixed-sentence condition and a varied-sentence condition. The fixed-sentence condition presented two tokens of the same sentence recorded by either one talker or two different talkers. In this condition, the linguistic content of the two sentences was held constant. The varied-sentence condition presented pairs of different

sentences recorded by either the same or different talkers. In this condition, the linguistic content varied within each pair of sentences. Talker discrimination is easier in the fixed-sentence condition because the linguistic content is the same, but is more difficult in the varied-sentence condition because children must inhibit linguistic processing of the lexical and semantic content in order to attend to the indexical properties of the two signals. The NH children completed the task without any acoustic degradation so they only received the varied-sentence condition since Cleary and Pisoni (2002) assumed performance would be at ceiling on the fixed-sentence condition.

Results revealed that CI children performed significantly above chance on the fixed-sentence condition. On the varied-sentence condition, NH children had very little difficulty discriminating talkers, while CI children performed more poorly and close to chance. Cleary and Pisoni (2002) also found that the CI children's performance on the fixed-sentence condition of the talker discrimination task was significantly correlated with performance on both open- and closed-set speech perception tasks. This pattern of results suggested that the CI children who are better at discriminating voices also have overall better speech perception scores.

Cleary, Pisoni, and Kirk (2005) further investigated talker discrimination abilities in CI children by using an adaptive version of the original Cleary and Pisoni (2002) task. In this study, children were told to make judgments on the similarity of voices in fixed- and varied-sentence conditions as the talker's voices were adjusted in small increments of 0.5 or 1 semitone(s). They found that while a small number of the CI children performed similarly to NH children, overall, the task was much more difficult for them to complete. Some of the CI children were unable to complete the task altogether. CI children had a

more difficult time discriminating between talkers, which the authors interpreted to mean that these children might have more poorly defined talker-category boundaries. Taken together, these two studies suggest that talker discrimination task is challenging and may be a useful tool for measuring auditory attention and speech perception abilities in CI children.

In addition to auditory attention, we were also interested in understanding the relations between short-term memory and vocoded speech perception. Short-term memory is the memory system that stores limited amounts of information for a short period of time (Baddeley, 2012; Cowan, 2008; Unsworth & Engle, 2007). Short-term memory has been shown to have an important foundational role in speech perception and language acquisition (e.g. Baddeley, Gathercole, & Papagno, 1998; Frankish, 1996; Gathercole, Service, Hitch, Adams, & Martin, 1999; Jacquemot & Scott, 2006; Jusczyk, 1997; Pisoni, 1975). CI users show delays and deficits in short-term memory compared to their NH peers (Dawson, Busby, McKay, & Clark, 2002; Harris et al., 2013; Pisoni & Geers, 2000) which ultimately affect their speech and language processing and development.

Short-term memory is commonly assessed with immediate memory span measures such as forward digit span or word span (Richardson, 2007; Wechsler, 2003). These methods require an individual to retain item and order information over a short period of time before recall of the information is required. Digit spans are frequently used as an index of short-term memory capacity and have consistently revealed strong relations with performance on a wide range of language measures in deaf children who have received CIs. Numerous studies have found significant correlations between digit

spans and measures of open-set and closed-set spoken word recognition (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003; Pisoni & Geers, 2000; Pisoni et al., 2011), speech perception (Pisoni et al., 2011), speech intelligibility (Pisoni & Geers, 2000; Pisoni et al., 2011), vocabulary (Fagan, Pisoni, Horn, & Dillon, 2007; Pisoni et al., 2011), language comprehension (Pisoni & Geers, 2000), reading (Fagan et al., 2007; Pisoni & Geers, 2000; Pisoni et al., 2011), verbal rehearsal speed (Burkholder & Pisoni, 2003), and nonword repetition (Pisoni et al., 2011). These findings are not limited to clinical populations, however. Recently, Osman and Sullivan (2014) reported that digit spans of NH children were significantly correlated with performance on speech perception tasks performed in noise. Taken together, these findings suggest a central role for short-term memory in spoken language processing.

As noted earlier, research with CI children has established the importance of auditory attention and short-term memory in speech and language measures, but very little research has investigated these areas of cognition in spectrally-degraded vocoded speech perception. Only one study to date has used any cognitive processing measures with vocoded speech. Eisenberg et al. (2000) had two groups of NH children (5-7 and 10-12 years of age) and a group of NH adults complete digit span tasks under varying amounts of acoustic degradation and then correlated their performance on the vocoded digit span task with performance on several different speech perception measures. They found a statistically significant positive correlation between digit span under 8-channel simulation and a language quotient derived from the Peabody Picture Vocabulary Test (PPVT) that controlled for age. The purpose of the present study was to fill a gap in the literature by further investigating the relations between auditory attention and short-term

memory with vocoded word recognition in NH children. We aim to expand on previous findings by investigating associations between neurocognitive measures and vocoded speech perception tasks, which has not been previously explored before even though earlier research has suggested the involvement of neurocognitive influences on performance.

Methods

Participants

These are same participants reported on in the previous chapter. Thirty-seven typically-developing monolingual English-speaking children (15 females, 22 males) from 5;2 years (years; months) to 13;3 years of age ($M=12;4$ years; $SD=2;7$ years) were recruited for this study. The majority of the sample was Caucasian ($n=33$), with the remaining identified as either Native Hawaiian/ Pacific Islander ($n=2$) or more than one race ($n=2$). Six children had to be excluded for the following reasons: technical problems ($n=2$), noncompliance ($n=3$), and reported speech delays ($n=1$). Thirty-one children remained between 5;9 years and 13;3 years of age ($M=10;0$ years, $SD=2;4$ years; 12 females, 19 males). Based on parent-report, all children had normal hearing and vision and no diagnosed cognitive/developmental delays. All children were recruited through an IRB approved departmental subject database. The majority of the children that participated in this study were from a moderate socioeconomic status: 19% reported incomes less than \$50,000; 58% reported incomes within the \$50,000-\$100,000 range; 6% reported incomes within the \$100,000-\$150,000 range; 10% reported incomes within the \$150,000-\$200,000 range; and 6% reported incomes greater than \$200,000. All

children included in data analyses passed a pure-tone hearing screening at 15 dB between 250-4000 Hz to verify hearing within normal limits.

Equipment

Speech perception testing was carried out in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. A high-quality Advent AV570 loudspeaker was located approximately two feet from the listener. A Radio Shack Digital Sound Level Meter was used to verify stimulus presentation levels over loudspeaker at 65 dB using C-Weighting. All stimuli used in the speech perception, digit span, and symbol span tasks were presented using programs run on a Power Mac G4 Apple computer with a Mac OS 9.2 using Psyscript (Bates & D'Oliveiro, 2003). A 12" Keytec LCD Touch Monitor was used to present visual stimuli. The colored touchscreen presented stimuli at a brightness level of 150 cd/m² and a contrast ratio of 100:1. During presentation of the visual stimuli, participants were seated at a table directly in front of the touchscreen. The touchscreen's presentation angle was 120°.

Vocoded Stimuli

Spectrally-reduced speech was created using techniques described in Shannon et al. (1995) and Eisenberg et al. (2002). Original recordings of unprocessed speech stimuli were obtained for the replication of Experiment 2 of the Eisenberg et al. (2002) paper. AngelSim (TigerCIS), an online CI speech-processing program, was used to custom-vocode speech stimuli. The original speech signals were processed to four spectral channels with bandwidth frequencies set at 300, 722, 1528, 3066, and 6000 Hz using a noise-vocoded setting with white noise as the carrier type (See Table 3.1 for division of frequencies for each channel).

Performance Measures

Word Intelligibility by Picture Identification- 2nd Edition (WIPI)

The WIPI test is a closed-set word recognition test (Ross, Lerman, & Cienkowski, 2004) that was used to familiarize the participants with vocoded speech. Each participant listened to List A, which consisted of 25 vocoded words presented over a loudspeaker at 65 dB. All participants responded by pointing to one of six pictures that matched the word he or she heard (see Appendix C for example response sheet). This assessment was scored for accuracy but not included in any formal analyses investigating relations between neurocognitive measures and vocoded sentence perception.

Lexically Controlled Sentences

The stimulus list of lexically controlled sentences originally developed by Eisenberg et al. (2002) was used to assess the effects of word frequency and neighborhood density on word recognition in sentences. Eisenberg et al. (2002) created two lists of words based on their lexical properties: a lexically “easy” list and a lexically “hard” list. They selected and categorized words as lexically easy or hard using the computational methodology described in the Neighborhood Activation Model (Luce, 1986; Luce & Pisoni, 1998) and by Kirk, Pisoni, and Osberger (1995). Lexically easy words are high frequency words in English with low neighborhood densities (fewer phonetically similar words). Lexically hard words are low frequency words with high neighborhood densities (greater number of phonetically similar words). Each list consisted of 15 practice words followed by 60 test words produced by one female speaker. Using those words, Eisenberg et al. (2002) created two lists of 25 low predictability sentences (5 practice and 20 test sentences). Each sentence was five to seven words in

length and contained three key words from either the easy or hard list. The two lists were combined to create one set of 10 practice sentences and 40 test sentences that were also vocoded and presented in a randomized order. Practice trials always preceded test trials (see Appendix B for list of sentences). Vocoded sentences were played over loudspeaker at 65 dB and scored for number of key words correct. For this task, children were instructed to repeat what they heard. Children did not receive any feedback regarding accuracy of their response.

While Chapter 2 analyzed both words in isolation and words in sentences, Chapters 3 and 4 only analyzed data from the words in sentences condition. Since performance on words in isolation and words in sentences were highly correlated for both the child data ($r=.79, p<.001$) and the adult data ($r=.62, p<.001$), only words in sentences were chosen so that the use of context could be investigated. Words in isolation were not included in analyses to increase the power of statistical analyses because of the relatively small sample size.

Auditory Attention and Response Set Subtests (NEPSY-2)

The Auditory Attention (AA) subtest of the NEPSY-2 was used to obtain a measure of the participant's selective auditory attention and ability to sustain attention. During administration of AA, the participant listened to a three-minute series of 180 prerecorded words presented over a loudspeaker and was instructed to touch the appropriate colored circle when the target color word (red) was presented randomly on 30 of the 180 trials.

The Response Set (RS) subtest of the NEPSY-2 was used to assess the participant's ability to shift to and maintain a new set of complex instructions while

inhibiting previously learned responses by correctly attending and responding to matching or contrasting stimuli. During administration of the RS, the participant listened to a three-minute series of 180 prerecorded words presented over loudspeaker and either touched the color, a contrasting color, or did nothing when a target color word was presented on 36 of the trials. Appendix D provides an illustration of the response sheet used for both AA and RS tasks. Raw and scaled scores were obtained for each child. These two subtests can be administered to participants ranging in age from 5-16 years (AA) and 7-16 years (RS). Three children (1 five-year-old female, 1 six-year-old female, and 1 six-year-old male) were not administered the RS due to the age restrictions of the assessment. Both subtests are part of the Attention and Executive Functioning domain of the NEPSY-2 and have a mean scaled score of 10 and SD of 3 (Korkman, Kirk, & Kemp, 2007). The AA or RS subtest were presented in clear and were not vocoded.

Talker Discrimination

A talker discrimination task was used to assess auditory attention for indexical properties of vocoded speech. This task was modeled after the talker discrimination task originally created by Cleary and Pisoni (2002) to investigate the ability of deaf children with CIs to discriminate differences between talkers. In this task, participants heard pairs of short meaningful sentences selected from the Harvard Sentence lists (e.g. the juice of lemons makes fine punch) and were asked to make a judgment as to whether the speaker of the first sentence in each pair was the “same” or “different” from the speaker who produced the second sentence. Responses were recorded using a touchscreen monitor. Appendix E provides a picture of the computer response screen. We modified this task from the original procedure in the Cleary and Pisoni (2002) study to use vocoded speech.

The sentences were vocoded following the parameters described in the Eisenberg et al. (2002) paper. The key design feature of the talker discrimination task is that the listener is required to consciously ignore the lexical-symbolic linguistic information in the sentence and focus his or her attention on the indexical properties of the signal to make a same or different judgment based on the vocal source.

Two presentation conditions were used in the talker discrimination task: a fixed-sentence condition and a varied-sentence condition. During the fixed-sentence condition, the same sentence was used for all trials. Participants completed eight practice trials (four pairs) per condition with experimenter feedback using clear unprocessed speech prior to listening to the vocoded speech to verify that the subjects understood the instructions and task requirements. The practice trials consisted of two male talkers (Talker 1 and Talker 21) from the Indiana Multi-Talker Sentence Database (IMTSD) developed by Karl and Pisoni (1994). Two practice trials used the same talker and two practice trials used different talkers. The test trials followed the practice trials. The test trials consisted of three female talkers (Talkers 6, 7, and 23 from the IMTSD). There were a total of 24 sentences (12 pairs) of test trials. Six trials were the same talker (each talker paired with herself twice) and six trials were pairs of different talkers (each talker paired with the other twice). The varied-sentence condition followed the same structure except that each test pair was a unique combination of two different sentences. Appendix F shows a list of sentence pairings. To respond correctly on each trial, the listener must actively inhibit processing the linguistic content of the sentence and focus his or her attention on the talker's voice. All of the sentence and speaker pairings were fixed, but

the order of presentation was randomized. Sentences were played over loudspeaker at 65 dB.

Visual Digit Span (Forward)

A forward visual digit span task was used to obtain a measure of each participant's verbal short-term memory capacity. This task had three types of trials: familiarity, practice, and test. Trials were administered via touchscreen computer. During the familiarity trials, the participant saw a single digit (between 1 and 9) randomly presented on the touchscreen monitor. The visual digits appeared as a black number encased in a black box on a white backdrop in the center of the screen for one second. When the digit disappeared, the response screen appeared. The response screen displayed the digits, 1 through 9, in a 3x3 fixed grid format. Appendix G shows an example sequence of trial presentations for a set size of two. The participant was instructed to touch the number previously displayed on the screen. After the familiarity trials, the participant began the practice trials. During the practice trials, the participant saw a set of two and then a set of three single digits presented sequentially on the screen, each digit presented for a period of one second. The response screen then appeared and the participant was instructed to reproduce the numbers previously seen in the order in which they were presented. The participant had a window of five seconds after each presentation to respond before the experimental program advanced to the next trial. Each participant had to successfully complete the practice trials to proceed to the test trials. The test trials then began with a set size of two digits (i.e. list length of two). Each list length was presented twice and had to be correctly reproduced during one of the two trials before the list length increased by one digit on the next trial. When the participant

failed to correctly reproduce both trials at a given list length, the assessment was terminated.

The digit span task was scored for points correct. One point was awarded for each digit correctly reproduced in its correct serial order. For example, if a participant was presented with the digits “1...3...5” and responded with “1...4...5” the participant was awarded two points because the “1” and “5” were reproduced in their correct serial order. We chose to administer the digit span task in a visual format to obtain measures of verbal short-term memory capacity that were independent of audibility. Use of a manual touchscreen response also eliminated issues of variability in verbal output and response organization in speech motor control.

Symbol Span (Forward)

A symbol span task was used to assess a participant’s nonverbal short-term memory capacity. This assessment was administered using the same procedure and format as the visual digit span assessment except nine abstract black and white symbols were used as stimuli in place of the familiar digits. Appendix H displays an example sequence of trial presentations for a set size of two.

Procedures

All children were tested individually. The study was completed in one test session lasting about 1-1.5 hours. Parental consents and child assents, when applicable, were obtained prior to testing as per the guidelines of Indiana University’s Institutional Review Board. All assessments were administered in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. At the conclusion of the

experiment, all children received monetary compensation and two books along with numerous stickers that were distributed throughout the testing session.

Results

Auditory Attention and Response Set

Raw scores from the auditory attention ($N=28$, $M=28.68$, $SD=1.59$) and response set ($N=28$, $M=32.82$, $SD=3.45$) tests were used in Spearman's rank correlational analyses with the vocoded sentence perception measure. While Pearson product-moment correlations were used for consistency of the replication of Eisenberg et al. (2002) in Chapter 2, Spearman's rank correlations were used in Chapters 3 and 4 because of the relatively small sample size and to detect potentially nonlinear trends in the data. Three children were removed from the AA data set due to failure to demonstrate understanding of the task. No significant Spearman correlations were found between AA or RS and vocoded sentences (see Table 3.2).

Talker Discrimination Task

Figure 3.1 shows the distribution of scores for the fixed-sentence and varied-sentence conditions in the talker discrimination task. The x-axis represents the proportion of correct responses produced out of the 12 trials. As shown in this figure, the majority of children (96.7%) performed above chance on the fixed-sentence condition ($M=74.2\%$, $SD=16.3\%$), but only 64.5% performed above chance on the varied-sentence condition ($M=59.2\%$, $SD=16.4\%$). Age was strongly related to performance on both conditions (fixed-sentence: $r(31)=.57$, $p=.001$; varied-sentence: $r(31)=.41$, $p=.024$). As expected, performance on the fixed-sentence condition was significantly better than performance on the varied-sentence condition; $t(31)=4.76$, $p<.001$ (see Figure 3.2).

Children's performance on both talker discrimination tasks was significantly correlated with their ability to recognize vocoded sentences (see Table 3.2) with the fixed-sentence condition ($r=.51$, $p=.003$) being more strongly related than the varied-sentence condition ($r=.40$, $p=.025$).

Table 3.3 displays the children's error rates and types of errors in both the fixed-sentence and varied-sentence conditions. In the fixed-sentence condition, children showed a higher occurrence of "misses" responding "same" when the talkers were different. However, during the varied-sentence condition, children show a higher occurrence of "false alarm" errors responding "different" when the talkers were the same.

Visual Digit Span (Forward) and Symbol Span (Forward)

Mean scores for the forward visual digit span and forward symbol span are displayed in Figure 3.3. As determined by a one-sample t -test, children did significantly better on forward visual digit span ($M=30.1$, $SD=15.3$) compared to forward symbol span ($M=14.6$, $SD=11.3$); $t(31)=5.91$, $p<.001$. Both forward visual digit span and forward symbol span scores were correlated with performance on vocoded sentences (see Table 3.4) with digit span being more strongly related ($r=.43$, $p=.015$) than symbol span ($r=.38$, $p=.036$).

Discussion

The purpose of this study was to investigate the relations between auditory attention, short-term memory, and the perception of spectrally-degraded vocoded speech in NH children. Analyses revealed significant relations between performance on auditory attention and short-term memory tasks and a child's ability to recognize sentences that were vocoded to four spectral channels. This finding replicates previous research

suggesting that vocoded speech perception not only reflects peripheral processes, but also cognitive processes as well (Chatterjee et al., 2014; Conway, Bauernschmidt, Huang, & Pisoni, 2010; Davis, Johnsrude, Hervais-Adelman, Taylor, & McGettigan, 2005; Eisenberg et al., 2002).

One unexpected finding was that only one of the measures of auditory attention (the talker discrimination task) was related to how well a child perceived vocoded sentences. Neither of the two NEPSY-2 subtests was found to be correlated with performance on vocoded speech recognition. One explanation of this finding is that both the AA and RS tasks were too easy as performance was close to ceiling. The NEPSY-2 AA subtest is a detection task that requires a child to sustain attention by attending to a stream of spoken words and respond to the target words. The NEPSY-2 RS subtest also measured sustained attention in addition to set shifting, a form of response inhibition. With the exception of the three children who were excluded from analyses in the AA task, most children performed very well on both attention tasks, especially the AA task with the majority of children performing at ceiling level. As a result, the range of scores was very limited resulting in weak correlations.

Auditory attention as measured by the talker discrimination task did however, show significant relations to vocoded sentence perception. This finding suggests that a child's ability to attend to and discriminate differences between two vocoded talkers based only on indexical properties of speech is associated with recognition of vocoded sentences. It is important to point out here that both the fixed- and varied-sentence conditions were found to be significantly correlated to vocoded sentence perception. Although both conditions measure auditory attention, each condition also has a

substantial immediate memory component. Performance in the fixed-sentence condition taps into verbal short-term memory because the children have to detect a change between two sentences when the linguistic content remains constant. Consistent with the findings from the memory span data, short-term memory was strongly related to a child's ability to recognize vocoded sentences, which may be one reason why this task was so strongly correlated with performance on the vocoded sentence recognition task. In contrast, performance in the varied-sentence condition taps verbal working memory because the children now have to ignore differences in linguistic content between two different sentences while at the same time trying to detect similarities or differences between the talker's voices. This additional processing component increases the cognitive load on the child, making this condition more difficult. Increasing difficulty reduced variability by lowering overall performance, which may be one reason why the varied-sentence condition was not as strongly correlated to vocoded sentence perception as the fixed-sentence condition was. Additionally, because both the talker discrimination task and sentence perception task were vocoded, the relations found between the two measures may also be interpreted as reflecting individual differences in how the children process vocoded speech. Children that are better at perceiving vocoded speech would have an advantage on tasks using vocoded stimuli, such as the talker discrimination task.

Results from the talker discrimination task with NH children replicated findings from the earlier study with CI children carried out by Cleary and Pisoni (2002). Both studies found better performance on the fixed-sentence condition than the varied-sentence condition and stronger correlations between performance on the fixed-sentence condition and several conventional speech perception measures. A similar pattern was also found

in the error rates for each condition with a much stronger bias for committing false alarms during the more difficult varied-sentence condition. The present findings are theoretically and clinically important because they demonstrate that regardless of hearing status, reducing spectral information in the speech signal makes discriminating talkers more difficult, especially when the cognitive load is increased in the varied-sentence condition. These findings document the important role of cognition, specifically auditory attention, verbal short-term memory, and verbal working memory in perceiving spectrally-degraded vocoded speech. This is a significant contribution to the speech perception literature because it indicates that auditory attention and memory are important for spoken word recognition in suboptimal listening conditions such as when the signal is degraded during transmission. This new knowledge may be applied in the development of interventions for improving speech perception when the speech signal is presented in less than ideal listening environments. For example, if the signal is impoverished and cannot be enriched for perceptual processing then finding ways to improve attention or memory abilities may provide another avenue for improving speech perception. These results provide a new domain for future research and adds new knowledge to the growing body of literature in the field of vocoded speech perception (Chatterjee et al., 2014; Conway et al., in press; Davis et al., 2005; Dorman et al., 2000; Eisenberg et al., 2002; Eisenberg et al., 2000; Kronenberger & Pisoni, 2009; Maidment et al., 2014; Newman & Chatterjee, 2013; Shannon et al., 1995; van Heugten et al., 2013; Vongpaisal et al., 2012; Warner-Czyz et al., 2014).

Both measures of short-term memory also showed significant relations with performance on vocoded sentence perception measures. A child's ability to rapidly

encode and reproduce sequences of highly familiar items in serial order was associated with his or her ability to recognize vocoded words in sentences. In speech perception, verbal short-term memory plays an important central role in retaining the order of phonological and lexical information in working memory. Being able to encode, store, and remember serial order information about sequences of items is crucial considering the temporal nature of speech. This is especially important when only degraded phonological representations are available, as in spectrally-degraded vocoded speech perception tasks. Although the digits were presented visually, they were very likely to be verbally recoded for the purpose of rehearsal in short-term memory.

Although the symbol span was used as a measure of nonverbal short-term memory, it was also found to be correlated with performance on vocoded sentence recognition with a significance level close to that of the digit span task. Therefore, a child's ability to recall and reproduce the serial order of abstract visual objects was associated with his or her ability to recognize vocoded sentences. This was an unexpected finding because the symbol span task requires less verbal mediation than the digit span task. Although the symbol span task was originally designed to be a nonverbal measure of memory span, our informal observations suggest the use of verbal coding strategies by older children. To facilitate active verbal rehearsal, older children applied names to the visual displays to serve as verbal cues for rehearsal and recall. This might suggest that the two tasks may be tapping into similar aspects of short-term memory. Together, these findings and observations suggest that children with more efficient verbal coding strategies for encoding and remembering abstract visual information were able to apply more efficient strategies for recognizing vocoded speech. Also, because sentences

provide context cues and downstream support, it is possible that the ability to use context efficiently is related to the ability to recognize speech when less sensory information is available in the signal. As a result, the findings obtained from the symbol span task are confounded by the verbal coding carried out by the older children.

One limitation of this study is that it is a correlational study and, therefore, does not provide causal explanations between any of the performance measures. Future research should include additional analyses to examine interactions between variables and compare variance accounted for by each measure for a more thorough understanding of cognitive involvement. This research does, however, provide information regarding previously unexplored domains in vocoded speech perception, which is important for future research on the perception of degraded vocoded speech and individual differences in deaf children who use CIs.

Conclusions

The purpose of this study was to investigate the relations between auditory attention and short-term memory in vocoded speech perception in NH children. The findings obtained in this study are consistent with the existing literature suggesting that speech perception and cognition are closely interlinked systems (Burkholder & Pisoni, 2003; Deary, 1994; Harris et al., 2013; Johnson & Goswami, 2010; Pisoni et al., 2011). Speech perception involves multiple systems working together in a highly integrated fashion and is not reliant on a single cognitive or peripheral sensory component. More specifically, the present findings uncovered relations between auditory attention and short-term memory with degraded speech recognition. Understanding the relations of auditory attention and short-term memory in vocoded speech perception can provide

important insights into the specific aspects of cognition that are most important for recognizing degraded speech and these results will be especially relevant for listeners with hearing impairments. Knowing specific cognitive factors that may support successful speech perception and spoken word recognition will help in identifying children that may be susceptible to delays and provide earlier interventions that can include components not only aimed at improving the perceptual processing of speech but also cognitive processing. The present findings also provide new insights into understanding and explaining the enormous individual differences in the speech perception skills of deaf children with CIs by documenting the contribution of attentional control and short-term memory.

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Table 3.1. Frequency Bandwidths for the 4-Channel Vcoded Simulation

Spectral Channel	Lower Frequency Cutoff (Hz)	Higher Frequency Cutoff (Hz)	Channel Bandwidth (Hz)
1	300	722	422
2	722	1528	806
3	1528	3066	1538
4	3066	6000	2934

Table 3.2. Spearman Correlational Analyses of Auditory Attention Measures and Vcoded Sentence Perception Scores for Children

Auditory Attention Measure	Vcoded Sentences
NEPSY Auditory Attention	.34
NEPSY Response Set	.16
Talker Discrimination (Fixed)	.51**
Talker Discrimination (Varied)	.40*

Note. Speech perception measures reflected percent accuracy. Auditory Attention and Response Set reflect raw scores.

** $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)*

Table 3.3. Vocoded Talker-Discrimination Task: Miss Rates and False Alarm Rates Among Children (Percentages)

Type of Error	Fixed-Sentence Condition	Varied-Sentence Condition
Miss Rate	14.79	16.91
False Alarm Rate	11.54	23.11

Table 3.4. Spearman Correlations Between Measures of Short-Term Memory and Vocoded Sentence Perception Scores for Children

Short-Term Memory Measures	Vocoded Sentences
Digit Span (Forward)	.43*
Symbol Span (Forward)	.38*

Note. Speech perception measures reflected percent accuracy. Span measures scores reflect points per correct response.

** $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)*

Figure Captions

Figure 3.1 Talker discrimination scores displayed as proportion of correct responses out of the 12 test trials. Top panel displays a histogram of the number of correct trials for the fixed-sentence condition; bottom panel displays a histogram of the number of correct trials for the varied-sentence condition.

Figure 3.2 Mean scores for fixed-talker and varied-talker conditions in talker discrimination task. Children were significantly more accurate at identifying “same” or “different” talkers in the fixed-sentence condition compared to the varied-sentence condition. Error bars represent standard error.

Figure 3.3 Mean scores for forward digit span and forward symbol span tasks. Children were significantly more accurate at reproducing the serial order of visually presented digits compared to abstract visual symbols. Error bars represent standard error.

Figure 3.1.

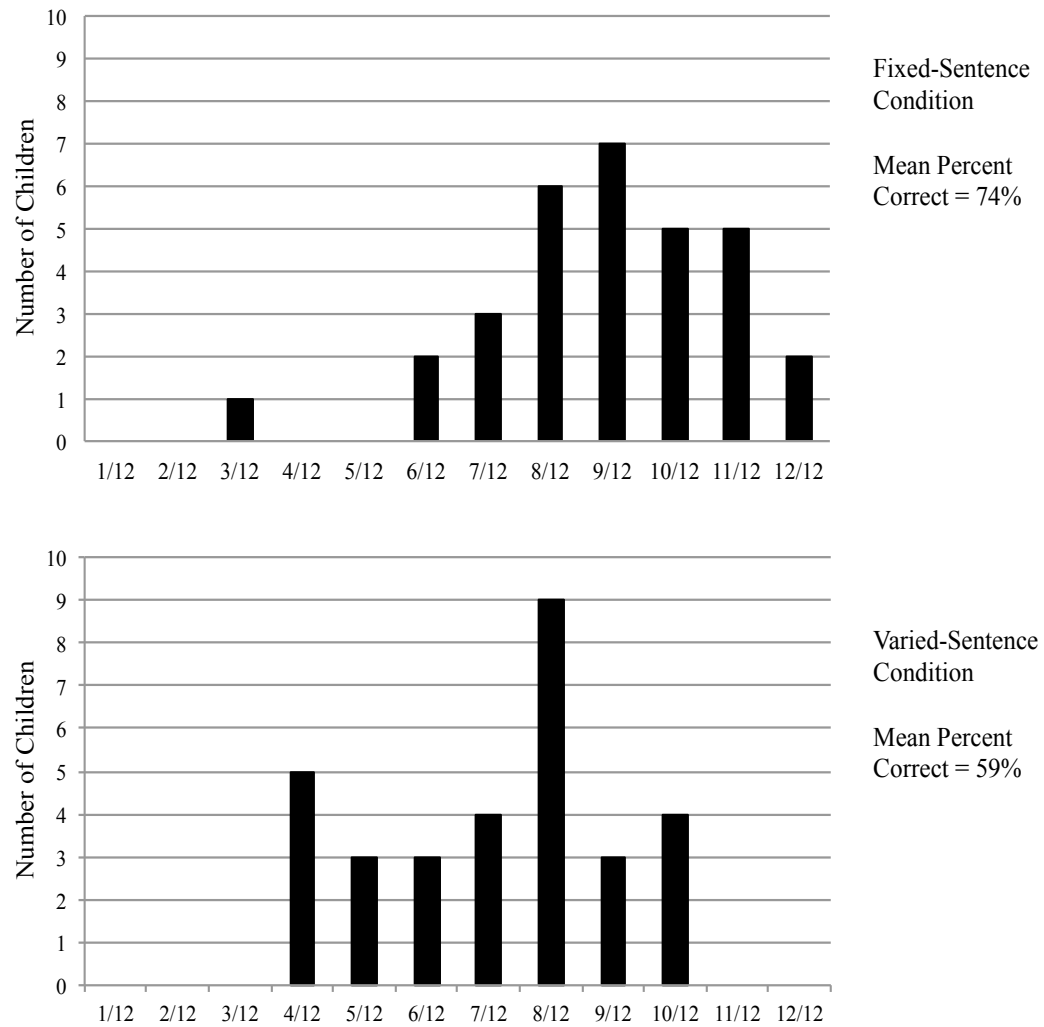


Figure 3.2.

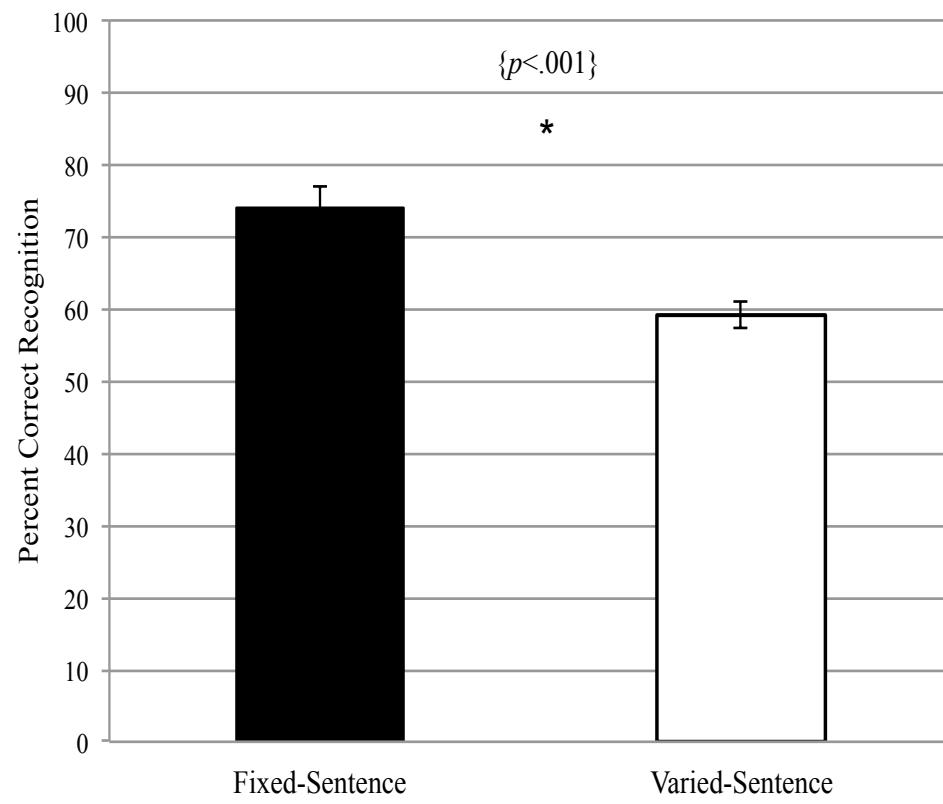
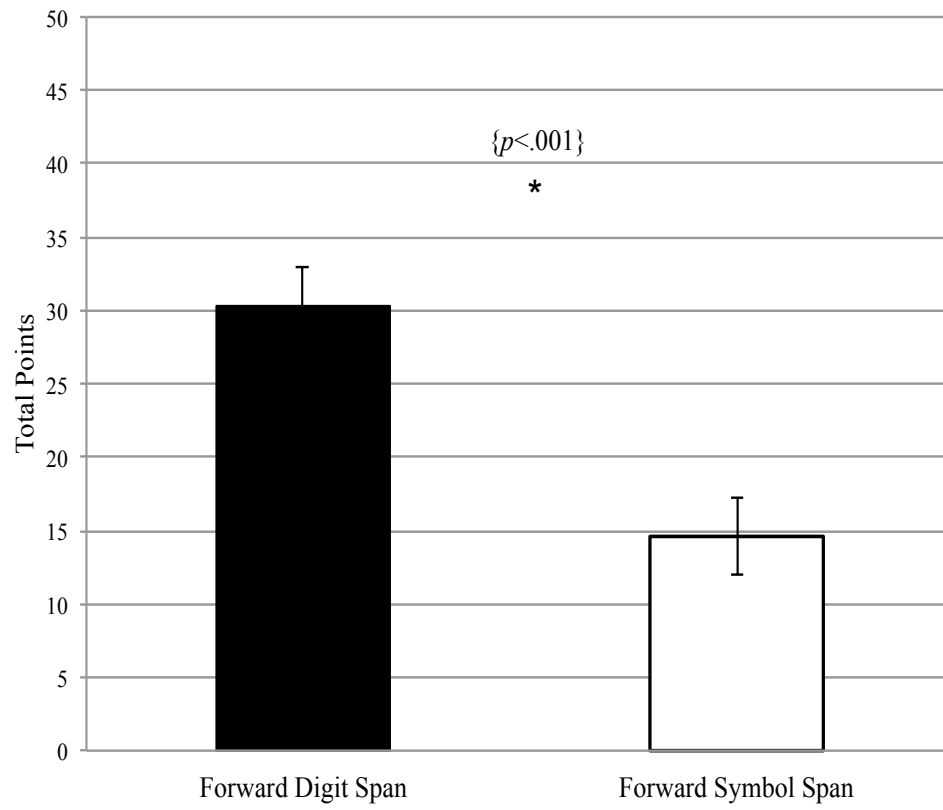


Figure 3.3.



CHAPTER 4

VERBAL LEARNING AND MEMORY STRATEGIES AS CORRELATES OF VOCODED SENTENCE PERCEPTION

Introduction

Humans have a remarkable sensitivity to patterns, statistical regularities, and the underlying sequential structure of natural languages (Conway & Pisoni, 2008; Gupta & Dell, 1999; Redington & Chater, 1997; Romberg & Saffran, 2010). This inherent sensitivity allows infants and young children to implicitly learn the complex rule system that underlies language through passive exposure and listening experience (Altmann, 2002; Chambers, Onishi, & Fisher, 2003; Jusczyk, 1997, 2002; Jusczyk & Luce, 1994). Through this type of statistical learning, children are able to obtain a great deal of knowledge about their native language including probabilistic phonotactics, syntax, word boundaries, and lexical organization, to name a few (Auer & Luce, 2005; Conway, Bauernschmidt, Huang, & Pisoni, 2010; Jusczyk, 1997, 2002; Saffran, 2003; Vitevitch & Luce, 1998; Yu, 2008). The ability to detect and process information sequentially develops early in life (Saffran, Aslin, & Newport, 1996) and is critical in the development of language because of its temporal nature (Dominey & Ramus, 2000; Romberg & Saffran, 2010; Rosen, 1992; Saffran, 2002; Tallal, Miller, & Fitch, 1993).

Several recent studies have suggested that children with cochlear implants (CIs) have difficulty with sequential learning and processing. Conway, Karpicke, Anaya, Henning, Kronenberger, and Pisoni (2011) found deficits in prelingually deaf children with CIs when compared to normal-hearing (NH) peers in performance on the NEPSY

“fingertip tapping” subtest that assessed motor-sequencing abilities. The authors also found that performance by the children with CIs on the sequential portion of the fingertip tapping motor-sequencing subtest along with the “dot location” subtest of the Children’s Memory Scale, a nonverbal visual-spatial learning and memory task, were related to language outcomes on the Clinical Evaluation of Language Fundamentals, 4th Edition (CELF-4). The children with CIs who were slower on the sequential fingertip tapping task and had lower scores on the dot location visual-spatial learning and memory task also had lower scores on the CELF-4, suggesting that poorer motor-sequencing and sequential spatial memory abilities in the children were related to poorer language outcomes (Conway et al., 2011).

In another study, Conway, Pisoni, Anaya, Karpicke, and Henning (2011) found deficits in the implicit learning of visual color sequences in children with CIs. The children in this study were asked to reproduce color sequences that were generated by an artificial grammar unknown to them. Learning was measured by improvement on the accuracy and length of their reproductions of novel grammatical sequences. Results revealed that NH children performed significantly better on novel grammatical sequences in comparison to ungrammatical sequences, as expected, but children with CIs were no better at reproducing the grammatical sequences than the ungrammatical sequences. This finding demonstrated that the children with CIs implicitly learned sequential patterns at rates that were delayed relative to their NH peers. Conway et al. (2011) also found that these implicit learning abilities were related to vocabulary development in the children with CIs, suggesting a link between the implicit learning of sequential patterns and language acquisition.

Several years ago, Conway, Pisoni, and Kronenberger (2009) proposed an “auditory scaffolding hypothesis” to explain the observed deficits in sequential learning in children with CIs. Because when we process speech and sound we also encode temporal patterns, the authors suggested that early experience with sound patterns helps to support the development of other cognitive abilities that are also temporal or sequential in nature; essentially, experience with sound creates scaffolding and knowledge structures for other sequential abilities to build on. Hearing-impaired children with CIs are not only delayed developmentally because of the cortical reorganization of their neural and cognitive systems, but they also receive less robust acoustic information from the environment compared to NH peers (Niparko, 2009; Waltzman & Roland, 2006). The underspecified acoustic input from their CIs make implicit learning from passive exposure more difficult which, in turn disrupts typical-developing auditory scaffolding processes (Conway et al., 2011).

In another recent study, Ulanet, Carson, Mellon, Niparko, and Ouellette (2014) assessed the simultaneous and sequential processing abilities of a group of young children with CIs. The goal of this study was to examine the relations between neurocognitive processing and language outcomes to better understand why some children with CIs have poorer outcomes on language tasks. A small number of children with CIs ($N=22$) were divided into two groups based on language scores obtained from the Comprehensive Assessment of Spoken Language (CASL) and either the Clinical Evaluation of Language Fundamentals (CELF) Pre-School-Second Edition (CELF-P) or the CELF Fourth Edition (CELF-4) based on the child’s age at the time of testing. Children were classified as either having language scores “below expectations” (i.e.

scores below the age-standardized mean) or “meeting expectations” (i.e. scores at or above the age-standardized mean). The Leiter International Performance Scale-Revised (LIPS-R), the Mullen Scales of Early Learning (MSEL), or the Bayley Scales of Infant Development- Second Edition (BSID-II) was also administered as a baseline measure to verify that the children were within the normal range on nonverbal IQ and developmental measures. The children with CIs were also tested with the Kaufman Assessment Battery for Children, Second Edition (KABC-II) to assess their ability to integrate verbal, visual, and/or spatial information (simultaneous processing abilities) as well as reproduce visual, motor, and/or auditory information sequentially (sequential processing abilities).

Ulanet et al. (2014) found that both groups of children with CIs were very similar to NH peers on measures that assessed simultaneous processing capacities. However, the group with language scores below expectations displayed reduced sequential processing capacities in addition to significantly lower language scores. Simultaneous processing scores were found to be positively correlated with nonverbal IQ scores, while sequential processing scores were found to be positively correlated with language scores. Ulanet et al. (2014) suggested that specific deficits in sequential processing might negatively affect language processing and development in this clinical pediatric population. In summary, these recent studies revealed disturbances and delays in sequential learning and processing in children with CIs that may be related to poorer language learning and memory abilities.

Almost all of the published research on learning and memory of sequentially-presented stimuli in children with CIs has used visuospatial stimuli or a single-presentation of verbal stimuli. Repeated exposures to visuospatial sequences have been

used to test implicit or explicit learning (Conway et al., 2010; Conway et al., 2011), but no published research to date has systematically assessed the underlying foundational components of learning and memory in children with CIs using multiple exposures to verbal material. The ability to encode, store, and retrieve verbal information that is acquired over several repeated exposures is termed “verbal learning.” The lack of knowledge about fundamental verbal learning skills and development in children with CIs is a significant limitation in our current understanding of language and memory development in this clinical population, for several reasons:

First, in daily experience and learning, children are frequently exposed to repetitions of verbal information, in order to enhance memory and learning. Teachers, parents, and peers frequently repeat important information that is provided in spoken language, rather than providing a single exposure. Thus, verbal learning based on multiple exposures is a common experience in real-world interactions and learning outside the laboratory and clinic. Second, children’s abilities to learn based on multiple exposures cannot be inferred from memory performance after only a single exposure (Delis, Kramer, Kaplan, & Ober, 1994). Without direct research using a verbal learning paradigm, the verbal learning processes and abilities of children with CIs is unknown. Third, the use of verbal learning paradigms in research allows for the investigation of critical influences on learning and memory that cannot be investigated using single-exposure paradigms, such as learning curve (improvement with repetition exposures), proactive and retroactive interference (influence of competing verbal material on memory for learned information), changes in memory strategies in learning over repeated exposures (e.g., serial recall strategies, semantic recall strategies), decay of previously

learned material over a long delay, and recognition (e.g., storage) vs. free-recall (e.g., retrieval) capacity. Investigation of these influences can provide a process-level understanding of influences on verbal learning and memory that goes well-beyond knowledge of verbal capacity alone. Finally, repeated-exposure verbal learning paradigms place additional demands on other neurocognitive functions that are not taxed in the same way by single-exposure memory paradigms, allowing for further understanding of the influence of neurocognitive functioning on language learning and development. Verbal learning paradigms demand more flexibility, sustained concentration, and active management of memory strategies than single-exposure memory paradigms, because subjects are provided with multiple exposures that allow for the use of shifting, actively-managed strategies (e.g., shifting from rote-serial memory strategies to semantic clustering strategies to enhance recall based on meaningfulness of content) based on experience with prior exposures to the verbal material. Such flexibility, concentration, and active control of thinking are hallmarks of executive functioning (Barkley, 2012).

Verbal learning and memory skills are inseparable components of language processing and development that may be associated with the development of speech perception skills, particularly under perceptually challenging conditions. The interrelations of verbal learning and memory skills with speech perception are likely to be complex and may include components of “bottom-up” processing in which basic, foundational speech perception skills support higher-order verbal learning and memory skills and/or “top-down” processing in which verbal learning and memory are higher-order abilities that support and promote speech perception skills. Theories of language

processing have shown that bottom-up and top-down models considered alone often do not fully account for the complexity of interrelationships between basic and higher-order processes in language processing (Stanovich, 1980). Rather, interactive models that incorporate both bottom-up and top-down contributions in a bidirectional, reciprocal model have received the most support in areas of language development such as reading (Stanovich, 1980, 1986).

Individual differences in speech perception skills, particularly under challenging conditions, may have a significant “bottom-up” impact on verbal learning and memory in NH children and children with CIs, in several potential ways: First, in the earlier chapters of this dissertation, individual differences in processing vocoded sentences were found to be related to measures of auditory attention and short-term verbal memory. Thus, auditory attention may be more efficient in children with better speech perception skills under challenging conditions, and their verbal memory capacity may be larger. To the extent that verbal learning requires both capacity and efficiency of foundational speech processing and short-term verbal memory, performance on speech perception tasks under challenging, degraded conditions such as vocoded sentences should predict stronger, more efficient verbal learning performance. Second, fast-automatic efficient processing of speech signals may free up resources for higher-order cognitive tasks used in verbal learning, such as the executive functioning skills described in the previous paragraph. Third, stronger speech perception skills suggest more robust lexical representations in long-term memory. Short-term verbal learning and memory would benefit from stronger, more robust representations of spoken language.

Verbal learning and memory skills may also provide “top-down” support of robust sentence perception under challenging conditions. Interactive-compensatory theories of language processing posit that when phonological stimuli are poorly encoded, individuals rely more heavily on other sources of information for word identification, such as meaning and context (Stanovich, 1980). Speech perception under normal conditions is very fast, automatic, and therefore less dependent on contextual cues. However, vocoded speech perception is slower and more effortful, requiring additional allocation of cognitive resources for attention, memory, and comprehension to assist with sentence perception. Thus, under challenging perceptual conditions such as vocoded speech, individuals are more likely to rely on and benefit from top-down contextual cues in sentences. The ability to rapidly access contextual cues during sentence perception draws heavily on effortful controlled verbal learning and memory strategies, which individuals use to remember linguistic information during sentence perception and to learn across sentences. This was exemplified by the perceptual learning that took place in the group of NH children during the vocoded sentence task described in Chapter 2. Therefore, consistent with interactive-compensatory models of top-down and bottom-up processing of language (Stanovich, 1980), we suggest that the relations between speech perception under challenging conditions and verbal learning and memory are reciprocal and bidirectional, with each supporting the other.

A better understanding of the relations between verbal learning and speech perception abilities under challenging conditions would provide highly novel and significant information that addresses a critical gap in our understanding of language development in both typically-developing and clinical populations. Specifically, an

understanding of the foundational building-blocks and influences on verbal learning in typically-developing children will improve models and theories of verbal learning and suggest specific targets for assessment and intervention to improve verbal learning. For clinical populations with speech perception challenges and delays such as children with CIs, increased knowledge of relations between speech perception and verbal learning will provide both descriptive data about verbal learning and memory development and enhanced understanding of potential risk factors contributing to speech perception and verbal learning. Finally, investigation of relations between speech perception under challenging conditions and specific verbal learning and memory processes (learning curve, semantic vs. serial strategies, primacy vs. recency effects, decay, etc.) will also provide a specific, processing-level explanation of the role of speech perception in verbal learning and memory.

In order to address these research questions, relations between vocoded sentence perception, verbal learning and memory processes, and language abilities were investigated in two groups of children: a group of early-implanted children with CIs and a group of NH children using vocoded speech to simulate the spectrally-degraded speech conditions experienced by children with CIs. To assess verbal learning and memory strategies in these two groups of children, we selected a well-known normed standardized assessment measure- the California Verbal Learning Test- Children's Edition (CVLT-C).

The California Verbal Learning Test- Children's Edition (CVLT-C) is a high-yield neuropsychological assessment method that provides information about how a child learns and recalls – that is, encodes, stores, and retrieves – lists of spoken words using a multi-trial free recall procedure. During administration of the CVLT-C, children are

presented with a list of 15 words (List A) spoken live voice, full-face by an examiner five separate times. List A consists of words drawn from three semantic categories: things to wear, things to play with, and fruits. After each of the five presentations of List A, children are asked to recall as many words from the list as they can in any order. This multi-trial free recall procedure provides information on short-term memory, rate of learning, and memory organization strategies implemented by the children. After the five learning trials are over, the children hear a second list of 15 words (List B) and are asked to recall words from this new list. List B consists of new words from three semantic categories: fruits, sweets, and furniture. List B is used to measure proactive interference in verbal learning and memory. After recalling List B (the distractor list), children are then asked to recall the words again from List A (without being read the word list again), which is used to measure short-delay free recall and assess retroactive interference. Children are then provided with the names of the three semantic categories for List A words and are asked to recall words from each category (short-delay cued recall). After a 20-minute delay, children are again asked to recall the words on List A, first in a free recall format and next in a cued recall format to obtain measures of long-delay recall and decay.

Using this administration format, the CVLT-C assessment provides valuable information about verbal learning and organizational strategies, serial-position effects, short-term and long-term free recall, memory decay, learning rate, vulnerability to intrusions and perseverations during free recall, and effects of proactive and retroactive interference. Because the CVLT-C provides a comprehensive examination of a child's basic verbal learning, episodic, and semantic memory capabilities, it is often used in

clinical settings to detect and diagnose memory impairments that may be related to learning disorders, neurological deficits, or traumatic brain injuries (Arroyos-Jurado, Paulsen, Ehly, & Max, 2006; Delis et al., 1994; M. J. Roman et al., 1998).

In addition to the numerous verbal learning and memory measures provided by the CVLT-C, because the CVLT-C is administered as a multi-trial free recall task, researchers can also analyze the serial position curves obtained in free recall to identify where learning takes place after each trial. During free recall tasks a U-shaped serial position curve is commonly observed when recall for items is plotted against the item's serial position in the list (Murdock Jr, 1962). The U-shaped serial position curve shows that items at the beginning (primacy) and end (recency) of the list are recalled more often than items in the middle of the list. Primacy effects are frequently observed in free recall because items at the beginning of the list are thought to receive more verbal rehearsal in memory than items in the middle or at the end of the list (Murdock Jr, 1962; Rundus, 1971; Rundus & Atkinson, 1970). Recency effects are also frequently observed because items presented at the end of the list are still assumed to be available for retrieval from immediate short-term memory (Murdock Jr, 1962; Rundus, 1971; Rundus & Atkinson, 1970).

To quantify these memory and learning effects, the CVLT-C scoring program produces primacy and recency scores by calculating the percentage of words recalled from the beginning and end (respectively) of the list; however, the CVLT-C scoring program averages across all of the five learning trials to obtain these two scores. In addition to looking at the overall primacy and recency scores from the CVLT-C, we also decomposed each of the five learning trials of List A and List B into primacy, middle,

and recency subcomponents to obtain a more precise assessment of specific areas of the serial curve where learning occurred in the list during each trial. Decomposing the learning trials of the CVLT-C into the three subcomponents of the serial position curve is informative because it not only provides information about the recall patterns of individual children but it also reveals differences in the rates of learning for each subcomponent of the curve and provides insight into the different processing mechanisms associated with each of the subcomponents.

Although the CVLT-C is a high-yield efficient methodology to assess verbal learning and memory processes, it has not been utilized with pediatric hearing-impaired populations or with typically-developing children in relation to speech perception under challenging conditions (vocoded sentence perception). In fact, to date, only one study in the published literature has used the adult version of the CVLT with a group of post-lingually deafened CI adults. Heydebrand, Hale, Potts, Gotter, and Skinner (2007) administered the CVLT to obtain pre-implantation measures of recall performance that were used to predict post-implantation performance on spoken word recognition. The authors created a composite variable for the CVLT from four of the individual verbal learning measures: recall after the first and fifth presentation of List A and recall of List A after short and long delays. The authors found that improvement on spoken word recognition was strongly associated with higher free recall scores on the CVLT composite measures and that the duration of hearing loss and verbal working memory scores (measured by a separate letter span task) accounted for the majority of variance in the CVLT scores.

Although the findings from the Heydebrand et al. (2007) study demonstrate the potential usefulness of the CVLT in a hearing-impaired population to uncover relations between verbal learning and memory and speech and language measures, the study did not utilize the full potential of the CVLT to provide much more specific, processing-level information about verbal learning and memory: Although the CVLT provides over 50 measures from raw and standardized scores, Heydebrand et al. (2007) only used four composite variables to measure their adult CI user's verbal learning and memory abilities. While the authors found significant results with the composite score based on four measures of free recall, they did not address more specific questions about processing-level contributions to these findings.

The experiments reported in this chapter investigated short-term verbal learning and memory and spoken word recognition in two populations: NH children and adults using spectrally-degraded vocoded speech (Experiment 1) and prelingually deafened children with CIs (Experiment 2). Using these two populations allowed us to examine differences in the relations between vocoded speech perception by NH children and speech perception in children with CIs with verbal learning and memory strategies. Data from NH adults were obtained to have benchmarks to assess differences between the two groups of children. Comparing the two groups of children was of particular interest because both groups received spectrally-degraded acoustic input in the speech perception tests, minimizing effects related to the reduced sensory input. These comparisons can provide insights into relations between individual differences in speech perception of degraded stimuli and verbal learning and memory strategies in the two groups. The two studies reported below used the CVLT-C to examine relations between spoken word

recognition and measures of verbal learning and memory. In the present experiments, we focused on the short-term, free recall trials of verbal learning and memory of the CVLT-C in order to investigate serial position effects. We predicted that speech perception scores would be related to several verbal learning measures primarily through short-term effects obtained on the CVLT-C.

Experiment 1

The purpose of this first experiment was to investigate the relations between vocoded sentence perception and verbal learning and memory strategies in a group of 31 NH children and a group of 31 NH adults. Children and adults were tested on spectrally-degraded sentences vocoded to four spectral channels using materials from Experiment 2 of Eisenberg, Martinez, Holowecky, and Pogorelsky (2002). Subjects also completed the California Verbal Learning Test- Children's Version (CVLT-C) in the standard administration format.

Methods

Participants

Normal-Hearing Children

These are same children reported on in the previous chapters. Thirty-seven typically-developing monolingual English-speaking children (15 females, 22 males) from 5;2 years (years; months) to 13;3 years of age ($M=12;4$ years; $SD=2;7$ years) were recruited for this study. The majority of the sample was Caucasian ($n=33$), with the remaining identified as either Native Hawaiian/ Pacific Islander ($n=2$) or more than one race ($n=2$). Six children had to be excluded for the following reasons: technical problems ($n=2$), noncompliance ($n=3$), and reported speech delays ($n=1$). Thirty-one children

remained between 5;9 years and 13;3 years of age ($M= 10;0$ years, $SD= 2;4$ years; 12 females, 19 males). By parent-report, all children had normal hearing and vision and no diagnosed cognitive or developmental delays. All children were recruited through an IRB approved departmental database. The majority of the children that participated in this study were from a moderate socioeconomic status: 19% reported incomes less than \$50,000; 58% reported incomes within the \$50,000-\$100,000 range; 6% reported incomes within the \$100,000-\$150,000 range; 10% reported incomes within the \$150,000-\$200,000 range; and 6% reported incomes greater than \$200,000. All children included in data analyses passed a pure-tone hearing screening at 15 dB SPL between 250-4000 Hz to verify that their hearing was within normal limits.

Normal-Hearing Adults

These are same adults reported on in Chapter 2. Thirty-one typically developing monolingual English-speaking adults (27 females, 4 males) from 18;10 years (years; months) to 25;5 years in age ($M=20;8$ years; $SD=1;7$ years) were recruited for this study. The majority of the sample was Caucasian ($n=30$), with the remaining identified as Asian ($n=1$). By self-report, all adults had normal hearing and vision and no diagnosed cognitive or developmental delays. Adults were recruited using IRB approved flyers posted throughout the Psychological and Brain Sciences department at Indiana University. All adults included in data analyses passed a pure-tone hearing screening at 20 dB SPL between 250-4000 Hz to verify that their hearing was within normal limits. Data from a group of adults were obtained to provide a benchmark comparison for performance for the NH children on the neurocognitive and speech perception measures.

Equipment

Speech perception testing occurred in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. A high-quality loudspeaker (Advent AV570) was located approximately two feet from the listener. A Radio Shack Digital Sound Level Meter was used to verify stimulus presentation levels over loudspeaker at 65 dB using C-Weighting. Speech perception stimuli were presented using programs run on a Power Mac G4 Apple computer with a Mac OS 9.2 using Psyscript (Bates & D'Oliveiro, 2003).

Vocoded Stimuli

Spectrally-degraded vocoded speech was created using the signal processing techniques described in Shannon, Zeng, Kamath, Wygonski, and Ekelid (1995) and Eisenberg et al. (2002). Original digital files of the unprocessed speech stimuli were obtained from Dr. Laurie Eisenberg for the replication of Experiment 2 of the Eisenberg et al. (2002) paper. AngelSim (TigerCIS), an online cochlear implant speech-processing program, was used to custom-vocode all of the speech stimuli. The original speech signals were processed by AngelSim to create four spectral channels with bandwidth frequencies set at 300, 722, 1528, 3066, and 6000 Hz using a noise-vocoded setting with white noise as the carrier type.

Performance Measures

Word Intelligibility by Picture Identification- 2nd Edition (WIPI)

The WIPI test is a closed-set word recognition test (Ross, Lerman, & Cienkowski, 2004) that was used to familiarize the participants with vocoded speech. Each participant listened to List A, which consisted of 25 vocoded words presented over loudspeaker at 65

dB and responded by pointing to one of six pictures that matched the word he or she heard (see Appendix C for example response sheet). This assessment was scored for accuracy and took approximately five minutes to administer.

Lexically Controlled Sentences

The stimulus set of lexically controlled sentences originally developed by Eisenberg et al. (2002) was used to measure the effects of word frequency and neighborhood density on word recognition. Eisenberg et al. (2002) created two lists of words based on their lexical properties: one lexically “easy” list and one lexically “hard” list. They selected and categorized words as lexically “easy” or “hard” using the methodology described in the Neighborhood Activation Model (NAM) developed by Luce and Pisoni (1998) and Kirk, Pisoni, and Osberger (1995). Lexically “easy” words are high frequency words in English with low neighborhood densities (fewer phonetically similar words). Lexically “hard” words are low frequency words with high neighborhood densities (greater number of phonetically similar words). Each test list consisted of 15 practice words and 60 test words produced by one female speaker. Using these 75 words, Eisenberg et al. (2002) then created two lists of 25 low predictability sentences (5 practice and 20 test sentences). Each sentence was five to seven words in length and contained three “key” words from either the easy or hard list. The two sentence lists were combined to create one set of 10 practice sentences and 40 test sentences that were also vocoded and presented in a randomized order. Practice trials always preceded test trials (see Appendix B for list of sentences). Sentences were played over a loudspeaker at 65 dB and scored for number of key words correct. For this task, children and adults were instructed to simply repeat what they heard. Neither group received any feedback

regarding the accuracy of their responses. This task took approximately 10 minutes to administer.

California Verbal Learning Test- Children's Version (CVLT-C)

The CVLT-C was used to obtain a detailed profile of the participant's verbal learning and memory abilities. The CVLT-C provided measures of multi-trial free recall, recognition, organizational strategies, serial position effects, perseverations and intrusions in recall, and proactive and retroactive interference. The CVLT-C consists of two parts. During Part 1, the multi-trial free recall phase, the participant was asked to recall in any order items from a list of 15 words (List A) that the experimenter read aloud using live voice during 5 learning trials. The 15 items on List A consisted of familiar English words drawn from three semantic categories: things to wear, things to play with, and fruits. After the five learning trials with List A, an interference task was presented, consisting of a new list of 15 words (List B) read by the examiner. List B contained 15 words drawn from three semantic categories: fruit, sweets, and furniture. List B was followed by the short-delay free recall and cued recall tasks of List A test items. During cued recall, children were asked to recall items from each of the three semantic categories of List A (given to the children as memory retrieval cues). After a 20-minute delay period during which the children completed nonverbal activities, the experimenter began administration of Part 2 of the CVLT-C. During Part 2, the participant was asked to recall List A items again (long-delay free recall), followed by cued recall of List A items. Finally, to measure recognition memory (an estimate of storage with minimal demands on retrieval), participants were provided with a list of 45 words consisting of the 15 List A words and 30 distractor words and were asked to indicate for each word if it was a

from List A. In the present study, we focused on the short-term, free recall trials of verbal learning and memory (Part 1) because speech perception was expected to be related to verbal learning primarily through short-term effects on free recall.

Several raw and scaled scores were obtained for each of the CVLT trials for all child participants: List A Trial 1 Free Recall, List A Trial 5 Free Recall, List B Free Recall, List A Short-Delay Free Recall (CVLT measures of Cued Recall and Long Delay measures were not analyzed for purposes of this study). Raw and scaled scores were also obtained for several CVLT process measures: Proactive Interference (decrement in performance resulting from the interference of previously learned material on the retention of new material; List B score minus List A Trial 1 Score), Retroactive Interference (decrement in performance resulting from the interference of new material on the retention of previously learned material; List A Short-Delay Free Recall Score minus List B Score), Intrusion Errors (any words recalled that were not on the target list), Percent Primacy Recall (percentage of recalled words that were from the first 4 words of List A, across Trials 1-5), Percent Recency Recall (percentage of recalled words that were from the first 4 words of List A, across Trials 1-5), Semantic Cluster Ratio (an index reflecting the degree to which semantically-related words were recalled in adjacent order), Serial Cluster Ratio (an index reflecting the degree to which words adjacent to each other in the word list as presented by the examiner were recalled in adjacent order by the participant), and Learning Slope (the slope of the regression line fit between data points reflecting the number of words correctly recalled for each trial on List A Trials 1 to 5). Only raw scores were obtained for these measures for adults because the CVLT-C was designed and normed for use with children under 17 years of age.

In addition to global scores obtained from the CVLT-C, we also focused on a subset of trials that provided specific information about different processes of verbal learning and memory. List A Trial 1 was selected because it measures the first exposure to the test materials and provides information about the initial memory strategies employed and short-term memory capacity. List A Trial 1 is also important because it is the child's first exposure to all of the test items on the list without having any prior knowledge of list length or three semantic categories. List A Trial 5 was also examined separately because it is the last exposure to the test items on List A and can provide measures of the final memory strategies employed as well as information regarding the amount of material learned after five repetitions. List B was examined because, aside from being the distractor list, it also provided a measure of proactive interference from the five presentations of List A.

The CVLT-C is a standardized test with norms for participants ranging in age from 5-16:11 years. Excluding the 20-minute delay, the CVLT-C took approximately 30 minutes to administer (Delis et al., 1994). The CVLT-C was administered live-voice by the examiner, with full face visible.

Procedures

All participants were tested individually. The study was completed in one test session lasting 1-1.5 hours. Parental and adult consents and, when applicable, child assents were obtained prior to testing as per the guidelines of Indiana University's Institutional Review Board. All assessments were administered in an IAC sound booth in the Speech Research Laboratory at Indiana University in Bloomington. At the conclusion of the experiment, all participants received monetary compensation. The

children received two books along with numerous stickers that were distributed throughout the testing session to maintain motivation and attention.

Results

CVLT-C Performance Overview

Figure 4.1 provides a summary showing the average number of words correctly recalled by the NH children and adult controls for each of the five learning trials of List A and List B along with an overall mean score averaged across the five learning trials. An independent samples *t*-test (two-tailed) was carried out to compare recall performance between children and adults and determine if there were any differences in the number of items recalled from List A. Adults recalled significantly more items from List A on all five learning trials compared to the children (Table 4.1). Both children and adults showed improved recall over the five presentations of List A. An independent samples *t*-test was carried out to compare learning slopes between children ($M=1.05$, $SD=.59$) and adults ($M=1.40$, $SD=.45$) to determine if there were any differences in the rate of learning of items from List A. Although both groups demonstrated learning over the five learning trials, the adults showed a faster learning rate compared to children [$t(60)=2.62$, $p=.011$], two-tailed].

Table 4.2 displays results from an independent samples *t*-test analysis comparing overall performance by the NH children and adults on the CVLT-C. Findings show that adults were significantly different on all performance measures except amount of PI, serial clustering behaviors, and primacy and recency scores. As shown in Table 4.2, adults had better recall scores on List A Trial 1, List A Trial 5, List B, and then List A after a short delay (SDFR). They were also less affected by RI and produced

significantly fewer intrusions during recall. Adults also showed stronger tendencies to semantically cluster information during recall (recall information by categories). They also learned items on the list at a faster rate compared to children, which is indicated by learning slope. Children showed stronger recency scores demonstrating a stronger bias to recall items from short-term memory compared to adults.

CVLT-C Free Recall and Serial Position Curves

To better understand where learning occurred during the five learning trials of List A, we decomposed the learning curve into primacy, middle, and recency subcomponents. The CVLT-C scoring program defined the primacy portion of a list as the first four items and the recency portion as the last four items of the list (Delis et al., 1994). The middle portion included items 5-11 of the list. To further analyze primacy and recency effects in greater detail, each subject's data were rescored in order to calculate a separate percent correct score of recall for the primacy, middle, and recency portions of the list (e.g., percentage of words in each portion of the list that were recalled by the subject) for each learning trial. A percent correct score was also calculated for the middle seven items of each list although the CVLT-C program did not originally analyze these serial positions.

Figure 4.2 shows the overall serial position curves for List A Trial 1 (top panel) and List A Trial 5 (bottom panel). Scores for children and adults are plotted in each panel. Both children and adults showed very similar patterns of free recall for List A Trial 1. While both groups showed increases in recall after five learning trials, the adults were close to ceiling on performance for List A Trial 5. Both groups also showed the conventional U-shaped serial position curves as expected during free recall tasks. To

reduce the variance and noise in Figure 4.2, Figure 4.3 displays serial curves showing the average number of items correctly recalled (percent correct) for each of the three subcomponents of the serial position curves (primacy, middle, and recency) for each of the five learning trials for List A (1-5) for the NH children and adults. Both children and adults showed a consistent U-shaped serial position curve across all five List A learning trials. Words from the primacy and recency portions of the list were recalled better than items from the middle portion of the list. Also, performance increased for each consecutive presentation of List A, demonstrating repetition-based verbal learning by both groups over the five learning trials (also shown in Figure 4.1). Figure 4.4 shows a comparison of the rates of learning for each of the three subcomponents of the serial position curve for both NH children and adults. The triangles and circles to the right in each panel represent the average percent recall of items in List B for NH adults and children, respectively. Primacy recall was greater than middle and recency recall at Trial 1 and peaked at Trial 3 for both children and adults. Recency recall and middle recall, on the other hand, showed steep learning curves from Trials 1-3 and continued improvement through Trial 5.

Figure 4.5 displays performance on List A Trial 1 (solid line) and List B (dashed line) for each of the three subcomponents of the serial curve for NH children (left panel) and adults (right panel). Effects from proactive interference (PI) can be seen by comparing recall performance on List B to recall performance on List A Trial 1. Effects of PI are evident when poorer recall performance is found for List B compared to recall performance on List A Trial 1. Children showed poorer performance on List B on the primacy and middle portions of the lists compared to List A Trial 1. Paired samples *t*-

tests were computed to determine if the difference in performance was statistically significant. Analyses revealed that performance on the primacy portion of List A Trial 1 ($M=51.61$, $SD=24.10$) was not significantly higher than performance on the primacy portion of List B ($M=44.35$, $SD=28.66$); $t(30)=1.04$, $p=.31$, two-tailed. However, performance on the middle portion of List A Trial 1 ($M=30.03$, $SD=16.68$) was significantly higher than performance on the middle portion of List B ($M=19.81$, $SD=14.75$); $t(30)=2.74$, $p=.01$, two-tailed. This means that children were affected by PI during recall of the middle portion of List B. Adults showed poorer performance on List B only on the middle portion of the list compared to List A Trial 1. Paired samples t -test were computed to determine if the difference in performance was statistically significant. Analyses revealed that while performance on the middle portion of List A Trial 1 ($M=39.77$, $SD=15.74$) was not significantly higher than performance on the primacy portion of List B ($M=28.61$, $SD=25.59$); [$t(30)=2.01$, $p=.054$, two-tailed], the difference approached statistical significance.

Relations Between CVLT-C and Vcoded Sentence Recognition

Spearman's rank correlations were calculated between performance on the vocoded sentences and several scores from the CVLT-C scoring program to get an overview of how degraded spoken word recognition was related to verbal learning and memory measures for the NH children (see Table 4.3). While Pearson product-moment correlations were used for consistency in the replication of the Eisenberg et al. (2002) study in Chapter 2, Spearman's rank correlations were used in Chapters 3 and 4 because of the relatively small sample size and to detect potentially nonlinear trends in the data. Children with better speech perception scores for vocoded sentences recalled more words

on the fifth learning trial (List A Trial 5, $r_s=.47$, $p=.007$), Trial B ($r_s=.44$, $p=.014$) and List A Short-Delay Free Recall ($r_s=.41$, $p=.021$). Better speech perception scores were also related to greater serial clustering during recall ($r_s=.43$, $p=.016$), higher primacy recall ($r_s=.37$, $p=.04$), less recency recall ($r_s=-.52$, $p=.002$), and fewer intrusion errors ($r_s=-.42$, $p=.018$). These findings indicated that children with better speech perception under challenging, degraded sound conditions use more serial, primacy strategies during verbal learning and have greater verbal memory and learning capacity.

Spearman's rank correlations were also calculated between NH children's performance on vocoded sentences and the three derived subcomponents of the serial curve for List A Trial 1, List A Trial 5, and List B (see Table 4.4). Children with better scores on vocoded sentences recalled more words from the primacy portion of List A Trials 1 and 5. Better perception of vocoded sentences was also related to better middle portion recall only for List A Trial 5. Recency recall was unrelated to vocoded sentence performance on List A, but was positively related to vocoded sentence performance on List B.

These findings suggest that robust vocoded speech perception skills may underlie efficient subvocal rehearsal, which is used preferentially to maintain words from the primacy portion of List A in memory. On the other hand, recency recall for List A is much less likely to be dependent on active rehearsal skills and therefore may relate less with individual differences in vocoded speech perception. The finding of a significant relationship between vocoded sentence performance and List B recency suggests that different strategies and processes may influence List B performance, possibly as a result of PI effects. Importantly, PI effects on List B performance were shown only in the

primacy and middle portions of the list (Figure 4.5), whereas recency performance improved on List B. Therefore, PI effects may interfere with the benefit of efficient speech perception skills for recall from the primacy portion of the list. Improvement in recency performance in List B may reflect greater use of active memory strategies on the list, possibly involving verbal rehearsal or more robust lexical representations supported by efficient processing of spoken language such as robust speech perception skills.

Discussion

In this experiment, subjects demonstrated several well-established characteristics of verbal learning and memory using the CVLT-C. NH children and adults showed a positive learning curve over five repetitions of a 15-word list, with adults showing a faster learning rate and greater recall performance than children. Specific analyses of the subcomponents of the serial position curves produced expected primacy and recency effects in learning words on the list in both NH children and adults. When the learning trials were broken down by items based on their serial position in the list and divided into the three subcomponents of the serial position curve (primacy, middle, and recency), both NH children and adults also displayed U-shaped serial curves over all trials. This finding verified that all participants displayed a normal pattern for free recall as found in previous research in typically-developed young adults (Cole, Frankel, & Sharp, 1971; Murdock Jr, 1962).

Interestingly, PI effects on List B were not observed for recency portions of the list in either children or adults, whereas PI effects were consistently found for words in the middle of the word list. Furthermore, children showed a PI effect for the primacy portion of the list, whereas adults did not. This finding suggests that the effects of PI are

dependent on the location of the test words in the list. Specifically, recency effects in learning appear to be strong enough that PI does not negatively impact words presented at the end of the list, whereas words in the middle of the list are particularly vulnerable to PI. Another explanation for this pattern is the development of new organizational strategies for free recall by the time the children get to List B in the test protocol. Because information from the beginning of the list is thought to receive more active rehearsal, resulting in more robust representations in memory, children began to recall information at the end of the list first while it was still in immediate memory before recalling the items from the early primacy part of the list. This creates an advantage for remembering items at the end of the list, as opposed to the beginning. This pattern can be seen in Figure 4.3 where items from the recency portion were recalled at higher rates than those in the primacy portion of the list as the learning trials for List A proceeded (specifically List A Trials 4 and 5).

The results of this experiment also demonstrate that vocoded speech perception and verbal learning and memory are strongly related in NH children. Performance on the vocoded sentence task was correlated with several measures of verbal learning and memory throughout the CVLT-C: number of words recalled after five exposures to a word list, number of words recalled from an interference list, and number of words recalled from the original list after presentation of the interference list. Thus, better sentence perception under challenging conditions is related positively with a broad set of measures of verbal learning and memory. These findings are consistent with the hypothesis that the processes used in verbal learning and memory may act as compensatory strategies to support speech perception under challenging conditions and,

conversely, that robust lexical representations of spoken words and fluid-efficient speech perception promote greater verbal learning and memory.

Importantly, the present results go beyond verbal learning and memory performance and also provide insight into relations between vocoded sentence perception skills and process measures of verbal learning and memory. Better vocoded sentence perception was related to greater serial clustering during free recall trials, and individuals with better vocoded sentence perception recalled more words from the early portion of the list (primacy) and fewer words from the later portion of the list (recency). Greater amounts of serial clustering and primacy recall are suggestive of the use of rote Type I rehearsal strategies for maintenance of verbal information in short-term memory (Rundus, 1971; Rundus & Atkinson, 1970). Verbal rehearsal is critical for maintaining information in memory as additional information is received and processed, and items at the beginning of a list typically receive more verbal rehearsal than items in the middle or at the end of the list (Atkinson & Shiffrin, 1968; Rundus, 1971; Rundus & Atkinson, 1970). Because children with more robust, efficient speech perception skills under challenging conditions process verbal information more rapidly and automatically, they may be better able to use rote-serial cognitive/subvocal rehearsal strategies when learning lists of words. Additionally, the ability to efficiently create more robust and stable long-term representations of spoken language facilitates both memory and learning of sequences of spoken words and perception of degraded spoken language stimuli. On the other hand, children with poorer speech perception skills may be more reliant on recency strategies in verbal learning and memory, which demand less active rehearsal and memory strategies for free recall.

Vocoded sentence perception performance was negatively correlated with CVLT-C Intrusion scores. This finding indicates that children with better speech perception under challenging conditions were less likely to recall words that were not on the actual studied word list (List A). Fewer intrusions suggest less confusion and substitution of words in the same phonological or lexical neighborhood, as a result of more highly specified and detailed representations of phonological and lexical information about spoken words in memory. Such a result is consistent with more accurate and robust encoding of verbal items and better cognitive control, which would be reflected in better vocoded sentence perception scores.

Additional findings of particular interest included the relations between the serial curve subcomponents and spectrally-degraded vocoded sentence perception (Table 4.4). Correlational analyses revealed significant relations between recalling words from the primacy portions of the list for List A Trial 1 and the perception of words in vocoded sentences. By List A Trial 5, performance on the middle portion of the list was also significantly related to vocoded sentence performance. This suggests a trend that relations between vocoded sentence perception and performance on word recall by serial location increased with more repetitions for List A. Such a finding is consistent with the hypothesis that children with more robust, efficient speech perception skills engage strategies of rehearsal of words in serial order beginning with the primacy portion of the list at the first trial and progressing serially to the middle portion of the list by the fifth learning trial. Interestingly, for the PI trial (List B), only recency recall performance was positively related to vocoded sentence perception. This suggests that children with more robust lexical representations of words engage different strategies during the PI list than

the original list. It may be that robust representations of words from List A, which are stronger in children with better speech perception skills, interfere with less efficient rote-primacy memory strategies on List B and cause greater reliance on recency effects.

Taken together, these findings suggest that being able to actively encode, rehearse, and retrieve spoken words in their original serial order helps with verbal learning, memory, and recall of words presented earlier in a sequence (primacy), which must be retained in the face of interference from later (recency) words. This same process may also be important for learning language. Children who are more proficient at rapidly transferring verbal information into memory with less interference from recency effects may develop better language learning skills that aid them in perceiving speech when less reliable acoustic-phonetic information is available in the speech signal. Children who rely more heavily on retrieval from recency in free recall may be less efficient in establishing stable robust lexical representations of degraded speech in long-term memory.

In summary, the results of this study demonstrate the presence of similar verbal learning curves for NH children and adults, which demonstrate effects of primacy, recency, and serial clustering on recall performance. Reciprocal, bidirectional relations between vocoded sentence perception and verbal learning were hypothesized because each of these abilities supports the other under challenging conditions and because both of these abilities are dependent on robust lexical representations of spoken language. Thus, efficient encoding, transfer, and retrieval of verbal information from memory are critical for both verbal learning and perception of spectrally-degraded vocoded speech. The core processes underlying verbal learning and memory are inseparable and closely

linked to processes used to recognize spoken words in sentences, especially spectrally-degraded vocoded sentences like the ones used by Eisenberg et al. (2002).

Experiment 2

The purpose of this experiment was to extend the findings obtained in Experiment 1 to investigate relations between speech perception and verbal learning and memory in a group of children with cochlear implants (CIs) and a comparison group of NH age-matched controls. Children were tested on measures of sentence repetition and verbal learning. Using children with CIs and age-matched NH controls allowed us to uncover possible differences in verbal learning capabilities and organizational strategies in memory in these two groups of children. Cochlear implants provide degraded, compromised, underspecified auditory input, which requires more controlled-effortful processing strategies during speech perception, compared to the automatic, fluid speech perception in NH children. Furthermore, children with CIs have compromised, underspecified phonological and lexical representations of spoken words resulting from a period of auditory deprivation before they received their CIs. As a result, their language skills are slower and more effortful even when the demands of audibility are removed. As a result, children with CIs must allocate more effortful, controlled resources to tasks such as speech perception and verbal learning and memory compared to NH children. The effects of effortful speech perception demands and additional allocation of resources on verbal learning and memory in children with CIs have not been studied and represent an important area to investigate because learning processes underlie all adaptive behaviors, especially speech perception and spoken language processing.

Methods

Participants

Cochlear-Implanted (CI) Children

A subset of data from children with CIs was obtained from a larger ongoing study investigating the long-term neurocognitive processes and speech-language outcomes (LTO) in deaf children with CIs at Indiana University School of Medicine in Indianapolis (Kronenberger, Colson, Henning, & Pisoni, 2014; Ruffin, Kronenberger, Colson, Henning, & Pisoni, 2013). This subset consisted of 23 monolingual English-speaking children with CIs (11 females, 12 males) from 9;3 years (years; months) to 16;7 years of age ($M=13;2$ years; $SD=2;5$ years). The majority of the sample was Caucasian ($n=21$), with the remaining identified as either Asian ($n=1$) or more than one race ($n=1$). The children with CIs were all implanted with multichannel CIs prior to 7 years of age ($M=2;4$ years) and had used the implant for 7 years or more ($M=10;9$ years). All children had a severe to profound bilateral hearing loss that was identified by age 3 or younger. Etiology of deafness included: unknown ($n=12$), genetic ($n=4$), auditory neuropathy ($n=2$), Mondini malformation ($n=2$), enlarged vestibular aqueducts ($n=1$), ototoxicity ($n=1$), and Meningitis ($n=1$). Family income was reported as follows: 4.3% (\$10,000-\$14,999), 4.3% (\$15,000-\$24,999), 8.7% (\$25,000-\$34,999), 8.7% (\$50,000-\$64,999), 13% (\$65,000-\$79,999), 8.7% (\$80,000-\$94,999), 39.1% (>\$95,000), and 13% did not report. To participate, children had to be enrolled in an auditory-aural rehabilitative program and/or education setting and did not have any additional developmental or cognitive diagnoses other than hearing loss. All children had nonverbal IQ scores greater

than or equal to 1 SD below the normative mean. Table 4.5 summarizes the demographic characteristics of these 23 children with CIs.

Normal-Hearing (NH) Age-Matched Control Children

A subset of data from NH age-matched control children was also obtained from a larger ongoing study investigating the long-term neurocognitive processes and speech-language outcomes (LTO) in deaf children with cochlear implants at the Indiana University School of Medicine in Indianapolis (Kronenberger, Colson, Henning, & Pisoni, 2014; Ruffin et al., 2013). This subset consisted of 21 typically-developing monolingual English-speaking children (13 females, 8 males) from 9;11 years (years; months) to 16;7 years of age ($M=13;4$ years; $SD=2;4$ years). The majority of the sample was Caucasian ($n=16$), with the remaining identified as either African-American ($n=2$) or more than one race ($n=3$). By parent-report, all children were monolingual native English speakers, had normal hearing and vision, and no diagnosed cognitive/developmental delays. Family income was reported as follows: 4.8% (<\$5,000), 14.3% (\$25,000-\$34,999), 14.3% (\$35,000-\$49,999), 14.3% (\$50,000-\$64,999), 14.3% (\$65,000-\$79,999), 4.8% (\$80,000-\$94,999), 28.6% (>\$95,000), and 4.8% did not report. The percentage of participants that were cochlear-implanted or NH did not differ by gender [$\chi^2(1, N=44) = .88, p=.35$], income [$\chi^2(9, N=44) = 8.26, p=.51$], or age [$t(42) = .16, p=.88$]. Independent samples t -tests revealed no significant difference in nonverbal IQ between children with CIs ($M=10.43, SD=2.45$) and NH children ($M=9.71, SD=2.85$); $t(42) = .90, p=.37$, as measured by the Geometric Analogies subtest of the CTONI-2. All NH children had nonverbal IQ scores greater than or equal to 1 SD below

the normative mean. All NH children included in data analyses had pure tone hearing screenings within normal limits as assessed by a hearing screening.

Performance Measures

Geometric Analogies Subtest of the CTONI-2

The Geometric Analogies subtest is part of the Comprehensive Test of Nonverbal Intelligence- Second Edition (CTONI-2). The CTONI-2 is a standardized test of nonverbal reasoning abilities (Hammill & Pearson, 2009) normed for individuals ranging from 6–89.11 years of age. During the Geometric Analogies subtest, a child must understand the relationship between the two practice items and then use that knowledge to identify the missing item in the test pair. The Geometric Analogies subtest has a mean score of 10 and SD of 3. Scaled scores were obtained for each child. The test took approximately 10 minutes to administer.

Harvard Sentence Test

A set of meaningful Harvard Sentences (IEEE, 1969) was presented through a recording to both the children with CIs and NH children. Both groups of children heard the sentences presented in the clear, as this was part of a larger study not employing the use of vocoded speech. The stimuli consisted of 28 meaningful phonetically-balanced sentences. Two practice sentences were administered prior to the test sentences. Each sentence contained five keywords for a total of 140 test keywords (e.g. Never kill a snake with your bare hands). Performance was based on number of keywords correct and scores were transformed into percent correct scores. The Harvard Sentence Test took approximately 10 minutes to administer.

California Verbal Learning Test- Children's Version (CVLT-C)

See Methods section of Experiment 1 for a description of the CVLT-C assessment.

Procedures

All participants were tested individually. Parental consents and child assents, when applicable, were obtained prior to testing as per the guidelines of the Indiana University School of Medicine Review Board. At the conclusion of the experiment, all participants received monetary compensation. Testing took approximately one hour to administer and was carried out by highly experienced ASHA-certified speech-language pathologists.

Results

CVLT-C Performance Overview

Figure 4.6 displays the average number of correct words recalled by both groups of children for each of the five learning trials on List A and List B of the CVLT-C and an overall average score for the learning trials of List A. Both groups of children demonstrated learning effects following repeated repetitions of List A. Although both CI and NH children showed similar patterns of repetition learning, the CVLT-C scores for the CI children were slightly lower than their NH peers on average and for all learning trials except List A Trial 1. Independent samples *t*-test revealed no significant differences between the two groups of children's scores on any of the learning trials of List A (Table 4.6). An independent samples *t*-test was also carried out to compare learning slopes between the two groups of children to determine if there was a difference in the rate of learning of items from List A following repetition. No significant difference was found between the learning rates of the CI children ($M=1.03$, $SD=.67$) and

NH children ($M=1.33$, $SD=.39$), [$t(41)=1.71$, $p=.095$], two-tailed]. However, inspection of learning curves in Figure 4.6 shows that the learning curve for the CI sample reached an asymptote at a lower value than the learning curve for the NH sample. Thus, the CI sample reached a peak number of words learned that was numerically lower than the NH sample, although statistical tests of this difference were nonsignificant.

Table 4.7 displays results from an independent samples t -test analysis comparing performance by children with CIs and NH children on the CVLT-C. While the majority of differences in performance were nonsignificant, NH children showed higher serial clustering scores compared to children with CIs indicating that NH children were more likely to recall information in the order it was presented on the study list.

CVLT-C Free Recall Serial Position Curve Analyses

As with the data from the NH children and adults in Experiment 1, each child's CVLT-C free recall data were rescored in order to calculate a percent correct score for free recall of items from the primacy, middle, and recency portions of the list for each learning trial. A percent correct score was also calculated for the middle seven items although the CVLT-C program did not provide this score. The free recall data from the CI children and their NH age-matched peers were also decomposed into three subcomponents (primacy, middle, and recency) for List A Trial 1, List A Trial 5, and List B. Figure 4.7 shows a summary overview of the serial position curves for List A Trial 1 (top panel) and List A Trial 5 (bottom panel) for the CI and NH groups, respectively. Both groups showed a similar pattern of free recall with the typical U-shaped serial position curve after first exposure to the test materials (List A Trial 1) and a less shallow serial position curve near ceiling levels of performance for List A Trial 5.

Figure 4.8 displays the smoothed serial position curves based on averaging the number of items correctly recalled (percent correct) in each of the three subcomponents of the list (primacy, middle, and recency) for each learning trial in List A (1-5) for both the CI (solid line) and NH (dashed line) children. Both groups of children displayed serial position curves with free recall accuracy increasing following consecutive learning trials of List A. Figure 4.9 shows a more detailed comparison of the rate of learning for each group by plotting average percent recall scores for both groups of children broken down by the three serial curve subcomponents. The circles and squares to the right in each panel represent the average percent of recall of items in List B for NH children and children with CIs, respectively. Figure 4.10 displays performance on List A Trial 1 and List B for each of the three subcomponents of the serial position curves for CI children (left panel), NH children (center panel), and the younger NH children from Experiment 1 (right panel) for comparison.

Figures 4.8 to 4.10 demonstrate several patterns in the learning curves of the CI and NH samples. At List A Trial 1, the CI and NH samples show very similar percentages of correct recall for words from the primacy, middle, and recency portions of the list. By Trial 3, however, the percentage of correct recall for primacy and middle portions of the list in the NH sample exceeds that of the CI sample, whereas recency performance remains similar (not significantly different). This suggests that differences in verbal learning between NH and CI samples influence earlier portions of the word list first, consistent with the finding from Experiment 1 which showed that better speech perception skills (which would be found in children with NH compared to those with CIs) were associated with better primacy (on Trials 1 and 5) and middle (on Trial 5) recall, but

not recency recall (Table 4.4). In Figure 4.11, effects of PI can be seen by comparing free recall performance on List B to free recall performance on List A Trial 1 for each of the three groups. Effects of PI result in worse recall performance for List B than for List A in the primacy and middle portions of the list for the NH children in both experiments, but not in the recency portion of the list. The CI children showed susceptibility to PI only on the middle portion of List B. They also displayed the same improvement in List B Recency recall as was shown by the NH samples.

CVLT-C and Speech Perception Measures

Spearman's rank correlations were calculated between performance on the Harvard sentences and the CVLT-C for both the CI and NH age-matched children (see Table 4.8). In the NH children's dataset, one significant correlation was uncovered between performance on the Harvard sentences and the CVLT-C Serial Clustering score ($r_s=.48, p=.03$). NH children who utilized more serial recall strategies performed better on word recognition in sentences. In the CI children's dataset, two significant correlations were observed. Children with CIs who had stronger performance on the Harvard sentences produced better CVLT-C List A Trial 1 scores ($r_s=.43, p=.04$) and had fewer intrusions on List A recall ($r_s=-.47, p=.02$).

Spearman's rank correlations were then calculated between performance on Harvard sentences and the three subcomponents of the serial curve for learning trials List A Trial 1, List A Trial 5, and List B (see Table 4.9). No significant correlations were found in the NH children's data between the Harvard Sentence Test scores and scores from the serial position curve subcomponents. However, significant correlations were found between performance on the Harvard Sentence Test and the recency component of

each of the three trials for the CI children (List A Trial 1 recency, $r_s=.60$, $p=.003$; List A Trial 5 recency, $r_s=.51$, $p=.013$; and List B recency, $r_s=.60$, $p=.002$). Children with CIs who had stronger sentence perception skills on the Harvard sentences had much stronger recall performance on test items from the recency portion of the two test lists.

Discussion

Children with CIs and NH children did not differ statistically in performance for words recalled on any trials of CVLT-C List A or List B, in contrast to consistent findings reported in the research literature showing poorer verbal short-term and working memory in children with CIs (Pisoni & Cleary, 2003; Pisoni & Geers, 2000; Pisoni, Kronenberger, Roman, & Geers, 2011). Although the trend for verbal learning across the five List A trials was for children with CIs to reach a ceiling level of performance that was lower than that for NH children (see Figure 4.7), the similarities in global performance on verbal learning and memory capacity between the CI and NH samples on the CVLT-C were striking given the significant auditory deprivation of the children with CIs. The discrepancy in findings between the present study and earlier research demonstrating short-term verbal memory deficits in children with CIs could be a result of several factors: Almost all of the prior research on short-term memory in children with CIs has used span tests that require serial recall lists of items that cannot be grouped semantically into meaningful chunks (such as digits), and the test items must be recalled in the same serial order as they were presented. The test items on CVLT-C use words that fall into three semantic categories that can be recalled in any order. Alternatively, the current study may not have been sufficiently powered to detect differences between the CI and NH groups; for example, numeric differences were evident between groups on

List A Trials 3-5 and on List B. However, this latter explanation would not account for the minimal differences between CI and NH groups found on Lists 1 and 2. Effect sizes in other studies of verbal short-term memory (Harris et al., 2011; Pisoni et al., 2011) suggest that the sample size in the current study was adequate to detect differences in free recall performance. Thus, the findings from the present study provide evidence that performance on CVLT-C verbal learning and memory in children with CIs cannot be inferred from performance on rote-sequential verbal short-term memory measures such as digit span. Additional research is needed to understand verbal learning and memory capacity in children with CIs in these two memory tasks.

Analyses of performance based on serial position of words in the list showed a characteristic U-shaped curve of performance in both the CI and NH samples overall and for all learning trials of List A. On later trials of List A, the NH sample learned words from the primacy and middle portions of the list at a faster rate than the CI sample, showing that much of the gain realized by the NH sample relative to the CI sample by Trials 4 and 5 came from performance improvement in the earlier portions of the word list. In Experiment 1, poorer speech perception of vocoded stimuli was associated with poorer performance during later verbal learning trials (Trial 5) only in the primacy and middle portions of the list. Like the NH children who received vocoded sentence perception stimuli in Experiment 1, children with CIs in this experiment have more speech perception challenges as a result of the impoverished, degraded signal provided by the CI. Thus, consistent with the findings from Experiment 1 on the effects of degraded speech perception on verbal learning, children with CIs showed poorer verbal

learning performance only for the primacy and middle portions of the test list by the later CVLT-C trials compared to NH controls.

The ability to efficiently process a degraded, impoverished speech signal may be related more to primacy and middle items of verbal learning than to recency items. This may reflect the greater importance of having more robust representations of verbal stimuli for earlier-presented items in a list of words. Alternatively, more efficient speech perception under challenging conditions may permit greater use of serial rehearsal strategies that allow for better performance for earlier-presented items in a list of verbal stimuli.

Analyses of the relations between sentence perception skills and verbal learning performance revealed several differences between the CI and NH samples. In the NH sample, serial recall scores correlated positively with performance on spoken word recognition measured by the Harvard Sentence Test. A similar finding was found for NH children in Experiment 1, with better performance on vocoded sentence perception associated with greater serial clustering during recall. It is likely that this pattern reflects a tendency in children with especially strong fast-automatic processing in sentence perception to use internal serial representations of verbal stimuli in learning (either actively rehearsed or stored as robust representations in memory) during recall.

For children with CIs, sentence recognition scores were positively related to their ability to recall verbal information at first presentation (List A Trial 1) and to the production of fewer intrusive responses during recall. Stronger immediate memory and fewer intrusions during free recall suggests that CI children with stronger spoken word recognition skills have more robust detailed memory representations for the test items

presented on the CVLT-C. For NH children, significant relations between sentence recognition, recency recall memory, and intrusions may be absent because almost all NH children have fast-automatic speech recognition skills: NH children displayed near ceiling performance on the Harvard sentences ($M=96.95$, $SD=3.17$). As a result, slight differences in their sentence recognition skills are unlikely to influence memory efficiency in the same way found for children with CIs, whose speech perception skills are more variable, capacity-demanding, and effortful.

When the primacy and recency data were analyzed separately for List A Trial 1, List A Trial 5, and List B, another differential pattern of findings was uncovered between the NH and CI groups. While no significant correlations were found in the NH children's data, the CI children who performed better on the sentence recognition task also showed a strong bias for recalling test items from the recency portion presented at the end of the lists. This finding is in sharp contrast with the results obtained from the NH children in Experiment 1 and suggests that CI children with stronger speech perception skills may display a bias in processing and depend more heavily on retrieval of items from short-term auditory memory (e.g., recency) for processing of verbal information, even after many years of cochlear-implant use. It may be that the ability to create robust representations from degraded auditory sentences for children with CIs is similar to the memory representations accessed from the recency portion of a serial position curve. Memory for items in earlier portions of the list, in contrast, would require active rehearsal and maintenance in the face of competing stimuli from the latter portion of the list, which may rely on a different set of strategies in children with CIs. Clearly, more research is needed to investigate the relations and reciprocal influences of speech perception and

verbal learning in children with CIs; earlier findings about verbal working memory or inferences from results with NH samples under spectral degradation do not appear to be appropriate for understanding verbal learning performance in samples of children with CIs, especially deaf children who have used their CIs for long periods of time.

General Discussion

The two studies reported in this chapter investigated (1) characteristics of verbal memory and learning in NH and CI samples and (2) relations between the perception of spectrally-degraded speech and core verbal learning and memory processes. The investigation of relations between speech perception under challenging conditions and verbal learning and memory is critical to understanding the links between bottom-up and top-down cognitive processing and how they influenced speech perception and verbal learning skills. Specifically, verbal learning and memory are core higher-order cognitive functions underlying language development and use, which may be related to speech perception skills. We hypothesized that perception of spectrally-degraded speech and verbal learning and memory processes would be bidirectionally related because of (1) bottom-up influences whereby more automatic-fluid speech perception facilitates efficient verbal learning and memory; and (2) top-down influences whereby stronger lexical representations of words in verbal learning and memory allow for more robust perception of degraded speech signals. A correlational method was used in this research as a first step for establishing and investigating relations between these components of cognitive processing, providing support for the hypotheses and ideas for future directions for research.

The first study assessed vocoded speech perception in NH children and NH adults. The second study investigated speech perception in children with CIs and a group of age-matched NH controls. The results obtained with the CVLT-C provided new insights into how several core foundational measures of verbal learning and memory strategies are related to degraded spoken word recognition in both children with CIs and NH children listening to an acoustic simulation of a CI using spectrally-degraded vocoded speech.

Among the novel, theoretically significant findings from this research were several differences found in how CI and NH children and adults encode and retrieve verbally presented information. Although all groups showed characteristic U-shaped serial position curves during the multi-trial free recall tasks of the 15-item lists on the CVLT-C, groups who were more proficient in speech perception skills showed faster rates of repetition-based learning and greater free recall. In Experiment 1, adults remembered significantly more CVLT-C words and had a faster learning rate than NH children. In Experiment 2, NH children showed numerically greater recall performance and faster learning rate, although the differences were nonsignificant. These findings are consistent with stronger speech perception skills being related to better verbal learning and memory scores on a multi-trial free recall task.

A second set of findings demonstrated differences in verbal learning and memory based on the serial position of words in the list. For NH children in Experiment 1 and 2, performance on primacy words was stronger than middle and recency words for the first 1-2 exposures to the word list. However, words in the recency and middle positions of the list showed steeper learning curves than primacy and continued improvement through trial 5. Although a similar pattern of learning was shown by children with CIs, the CI

sample had a slower rate of learning for the primacy and middle portions of the word list than the NH sample, while recency learning rate was comparable between the two groups (Figure 4.9). This finding suggests that weaknesses in verbal learning in CI compared to NH samples are greater for words presented earlier in the list. This finding is consistent with the results reported in Experiment 1 showing that speech perception skills are positively associated with primacy and middle free recall but not recency free recall.

Relations between verbal learning and memory and sentence perception skills were observed in both experiments, as hypothesized. For NH children listening to vocoded sentences and for children with CIs using Harvard sentences in quiet, better speech perception was related to better CVLT-C word recall and fewer intrusion errors, consistent with models linking speech perception under challenging conditions and the processes underlying verbal learning performance. However, several differences in relations between sentence perception and verbal learning performance were also found between NH and CI samples. In the CI sample, for example, positive relations between sentence perception skills and verbal memory capacity were found for List A Trial 1, whereas in the NH sample under vocoded conditions, sentence perception performance was related to List A Trial 5, List B, and Short-Delay Free Recall. However, this discrepancy may be due to limited power in the statistical analyses, because the sentence perception-verbal learning correlations for the other trials for each group were in the predicted direction but did not approach significance. Also, the NH controls approached ceiling on the sentence recognition task in quiet.

A more substantial contrast between CI and NH results was found in relations between sentence perception and use of serial recall strategies in free recall, which were

strongly related in the NH sample under both vocoded (Experiment 1) and normal listening (Experiment 2) conditions but were unrelated in the CI sample. It may be that serial recall strategies are especially difficult for children with CIs because of possible underlying sequential processing deficits (Conway et al., 2010; Conway, Karpicke, et al., 2011; Conway, Pisoni, et al., 2011) and because of compromised lexical representations of spoken words. As a result, free recall in children with CIs may be reflected more in recency recall strategies (Figure 4.9) that are less dependent on active serial memory maintenance strategies such as verbal rehearsal. Therefore, CI children may rely more heavily on recency memory because they have less efficient verbal rehearsal and organizational strategies to help them transfer underspecified spoken words from auditory short-term memory into long-term memory in a brief period of time during a multi-trial free recall task.

There are several limitations to this research that should be considered when interpreting the results. First, the NH children using vocoded speech from Experiment 1 and the NH children in Experiment 2 were different demographically. The NH children in Experiment 1 were, on average, 3 years younger than the group of CI children and their NH age-matched controls used in Experiment 2. We did not control for age in the analyses, which is something to consider in future research. Also, the two studies used different stimulus materials to measure spoken word recognition, and the sentence stimuli were vocoded only in Experiment 1. As a result, the performance of NH children in Experiment 2 on the Harvard sentences, which were presented in unprocessed form, was near the ceiling, with very low variability. This latter characteristic may have influenced some of the correlational results of Experiment 2 because of the restricted variance in the

sentence scores. The CI children, on the other hand, received degraded auditory stimuli for both the sentences and for the CVLT-C, as a result of limitations inherent in their CIs.

An additional limitation is the correlational design of this study, which prevents drawing any causal conclusions. The associations between sentence perception and verbal learning skills suggest that there is a relationship that should be further investigated but the present results do not provide evidence to support specific, processing-level explanations at this time. Future research should address these processing-level questions using experimental designs. Lastly, because of the small sample sizes in all three groups, some analyses might not have been powered sufficiently to detect small effects. Therefore, nonsignificant findings should be interpreted with caution, and the findings from this study should be replicated to test for robustness and reliability with larger sample sizes spanning a greater age range.

Conclusions

The results of these two experiments demonstrated associations between speech perception under challenging, degraded listening conditions, and performance on a standardized test of verbal learning and memory. Although both groups of children (CI and NH) could process the degraded acoustic input, the present research using novel measures of verbal learning and memory showed that cochlear-implanted and normal-hearing children processed (i.e. encoded, stored, and retrieved) verbal material in several fundamentally different ways in a multi-trial free recall learning task. These are clinically significant findings because they suggest the presence of bidirectional top-down and bottom-up relations between speech perception and verbal learning and memory. For NH children, findings indicate that speech perception under challenging

conditions may both promote and be supported by verbal learning and memory capacity and strategies such as serial recall revealed by clustering strategies. For children with CIs, findings suggest that stronger speech perception skills may be particularly important for recency recall and reduction of intrusion errors. Knowing more about the information processing dynamics and organizational strategies used in verbal learning and memory by NH children under challenging speech perception conditions and by deaf children with CIs is critical at this time for the development of novel interventions for at-risk children with CIs. The next step in this research is to provide a processing-level explanation for the associations observed between sentence perception under challenging conditions and verbal learning and memory skills measured in the free recall tasks like the CVLT-C. Future studies should include direct investigation of the role of top-down and bottom-up influences testing causal models and specific predictions using direct experimental manipulations of several known independent variables to established functional relations between speech perception with challenging degraded conditions and underlying the organizational processing and strategies routinely used to assess verbal learning and memory skills.

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Table 4.1. Independent Samples t-test Analyses Comparing Recall Between Normal-Hearing Children and Adults in Experiment 1

Variable	Children		Adults		df	<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
List A Trial 1	6.13	2.09	7.48	1.12	46	3.176	.003
List A Trial 2	8.26	2.38	11.06	2.08	60	4.94	<.001
List A Trial 3	9.48	2.59	12.52	1.65	51	5.59	<.001
List A Trial 4	9.94	2.73	13.03	1.78	52	5.29	<.001
List A Trial 5	10.52	2.86	13.48	1.63	48	5.017	<.001

Note. Recall is reported in raw scores (number of items recalled).

Table 4.2. Independent Samples *t*-tests Between NH Children and Adults on CVLT-C Performance Measures in Experiment 1

CVLT-C Variables	NH Children (<i>N</i> =31)		NH Adults (<i>N</i> =31)		df	<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
List A Trial 1	6.13	2.09	7.48	1.12	46	3.18	.003
List A Trial 5	10.52	2.86	13.48	1.63	48	5.017	<.001
List B	5.58	1.65	7.68	1.86	60	4.68	<.001
PI	-.55	2.20	.19	1.78	60	1.46	.15
SDFR	8.77	2.78	12.77	2.33	60	6.14	<.001
RI	-1.74	1.55	-.71	1.44	60	2.72	.009
Intrusions	5.77	6.02	1.23	3.14	45	3.73	<.001
Serial Clustering	2.26	1.43	3.4	3.32	41	1.75	.087
Semantic Clustering	1.35	.45	1.68	.72	50	2.23	.03
Learning Slope	1.05	.59	1.40	.45	60	2.62	.011
Primacy	29.19	4.99	28.65	3.50	60	.501	.62
Recency	30.65	7.77	27.94	3.44	41	1.78	.083

Note. PI (proactive interference) was computed by subtracting List A Trial 1 from List B.
RI (retroactive interference) was computed by subtracting List A Trial 5 from the SDFR
(short-delay free recall).

Table 4.3. Spearman's Rank Correlational Analyses Between Percent Recognition of Vcoded Sentences and the CVLT-C Performance Measures for the NH Children in Experiment 1

CVLT-C Variables	R_s -Value
List A Trial 1	.30
List A Trial 5	.47**
List B	.44*
Proactive Interference (PI)	.06
Short-Delay Free Recall (SDFR)	.41*
Retroactive Interference (RI)	-.09
Intrusions	-.42*
Serial Clustering	.43*
Semantic Clustering	.20
Learning Slope	.29
Primacy	.37*
Recency	-.52**

Note. Vcoded sentence recognition scores reflect percent accuracy. Proactive interference was computed by subtracting List A Trial 1 from List B. Retroactive interference was computed by subtracting List A Trial 5 from the Short-Delay Free Recall.

** $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)*

Table 4.4. Spearman's Rank Correlational Analyses Between Vcoded Sentences and Serial Position Curve Subcomponents of the CVLT-C for the NH Children in Experiment 1

CVLT-C Serial Position Curve Subcomponents		R_S -Value
List A Trial 1: Primacy		.51**
	Middle	.03
	Recency	-.02
List A Trial 5: Primacy		.43*
	Middle	.51**
	Recency	-.042
List B:	Primacy	.18
	Middle	.017
	Recency	.43*

Note. Vcoded sentence recognition scores represent percent accuracy.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Table 4.5. Characteristics of the Children with CIs in Experiment 2

Measure	<i>M</i>	<i>SD</i>	Range
Age	13.11	2.36	9.27–16.63
Age at Implant	2.29	1.08	0.69–4.66
CI Duration	10.82	2.45	7.29–15.01

Note. Age is given in years; Age at Implant: age at cochlear implantation in years; and CI Duration: duration of cochlear implant use in years.

Table 4.6. Independent Samples *t*-test Analyses Comparing Recall of List A Between Children with CIs and NH Children in Experiment 2

Variable	CI Children		NH Children		df	<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
List A Trial 1	7.35	1.97	6.86	2.29	42	.76	.45
List A Trial 2	9.65	2.48	9.86	1.77	42	.31	.76
List A Trial 3	10.13	3.66	11.43	1.66	31	1.54	.13
List A Trial 4	11.65	2.48	12.43	1.47	36	1.28	.21
List A Trial 5	11.57	2.52	12.62	1.66	42	1.62	.11

Note. Recall is reported in raw scores (number of items recalled).

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Table 4.7. Independent Samples *t*-tests Between Children with CIs and NH Children in Experiment 2

CVLT-C Variables	CI Children (<i>N</i> =23)		NH Children (<i>N</i> =21)		df	<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
List A Trial 1	7.35	1.97	6.86	2.29	42	.76	.45
List A Trial 5	11.57	2.52	12.62	1.66	42	1.62	.11
List B	6.83	2.25	6.62	1.50	42	.36	.72
PI	-.52	2.47	-.24	2.7	42	.36	.72
SDFR	9.96	3.65	11.10	2.51	42	1.20	.24
RI	-1.61	2.31	-1.52	1.97	42	.13	.90
Intrusions	5.83	9.32	3.2	3.64	41	1.18	.24
Serial Clustering	2.11	1.94	3.41	1.97	41	2.16	.036
Semantic Clustering	1.40	.47	1.38	.50	41	.13	.90
Learning Slope	1.03	.67	1.33	.39	41	1.71	.095
Primacy	29.70	6.04	29.95	3.80	41	.16	.87
Recency	30.78	6.23	28.90	3.86	41	1.16	.47

Note. *PI* (proactive interference) was computed by subtracting List A Trial 1 from List B. *RI* (retroactive interference) was computed by subtracting List A Trial 5 from the SDFR (short-delay free recall).

Table 4.8. Spearman's Rank Correlational Analyses Between Harvard Sentences and the CVLT-C Performance Measures for the CI and NH Children in Experiment 2

CVLT-C Variables	CI Children (<i>N</i> =23)	NH Children (<i>N</i> =21)
List A Trial 1	.43*	-.20
List A Trial 5	.23	-.047
List B	.39	.019
Proactive Interference (PI)	-.006	.21
Short-Delay Free Recall (SDFR)	.21	.22
Retroactive Interference (RI)	-.09	.29
Intrusions	-.47*	-.11
Serial Clustering	-.15	.48*
Semantic Clustering	-.11	-.26
Learning Slope	-.039	.29
Primacy	-.37	-.087
Recency	.26	-.25

Note. Speech perception measures represent percent accuracy. Proactive interference was computed by subtracting List A Trial 1 from List B. Retroactive interference was computed by subtracting List A Trial 5 from the Short-Delay Free Recall.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Table 4.9. Spearman's Rank Correlational Analyses Between Harvard Sentences and Serial Position Curve Subcomponents of the CVLT-C for the CI and NH Children in Experiment 2

CVLT-C Serial Curve Subcomponents	CI Children (<i>N</i> =23)	NH Children (<i>N</i> =21)
List A Trial 1: Primacy	.041	-.28
Middle	.30	.011
Recency	.60**	-.27
List A Trial 5: Primacy	-.13	-.18
Middle	.22	-.12
Recency	.51*	.19
List B: Primacy	.035	-.15
Middle	.13	.30
Recency	.603**	-.06

Note. Speech perception measures represent percent accuracy.

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed)

Figure Captions

Figure 4.1. Average number of words correctly recalled on the CVLT-C by the NH children and adults for each of the five List A learning trials and List B along with an overall mean score average across the five learning trials of List A in Experiment 1. Error bars represent standard error.

Figure 4.2. Top panel shows the serial position curve for List A Trial 1 showing the breakdown of average number of each item correctly recalled in Experiment 1. Bottom panel shows the serial position curve for List A trial 5 showing the breakdown of average number of each item correctly recalled in Experiment 1 with NH children and adults.

Figure 4.3. Average percent correct recall of items for each learning trial of List A from the primacy, middle, and recency portions of the serial position curve arranged by trials in Experiment 1 with NH children and adults.

Figure 4.4. Average percent correct recall of items from the primacy, middle, and recency portions of the serial position curve for all learning trails of List A and List B arranged by subcomponents in Experiment 1 with NH children and adults.

Figure 4.5. Average percent correct recall for serial position curve subcomponents of List A Trial 1 and List B for both NH children and adults in Experiment 1.

Figure 4.6. Average number of words correctly recalled on the CVLT-C by the CI children and NH controls for each of the five List A learning trials and List B along with an overall mean score average across the five learning trials of List A in Experiment 2. Error bars represent standard error.

Figure 4.7. Top panel shows the serial position curve for List A Trial 1 showing the breakdown of average number of each item correctly recalled in Experiment 2. Bottom

panel shows the serial position curve for List A trial 5 showing the breakdown of average number of each item correctly recalled in Experiment 2 with CI children and NH controls.

Figure 4.8. Average percent correct recall of items for each learning trial of List A from the primacy, middle, and recency portions of the serial position curve arranged by trials in Experiment 2 with CI children and NH controls.

Figure 4.9. Average percent correct recall of items from the primacy, middle, and recency portions of the serial position curve for all learning trials of List A and List B arranged by subcomponents in Experiment 2 with CI children and NH controls.

Figure 4.10. Average percent correct recall for serial position curve subcomponents of List A Trial 1 and List B for both CI children and NH controls in Experiment 2 and NH children from Experiment 1.

Figure 4.1

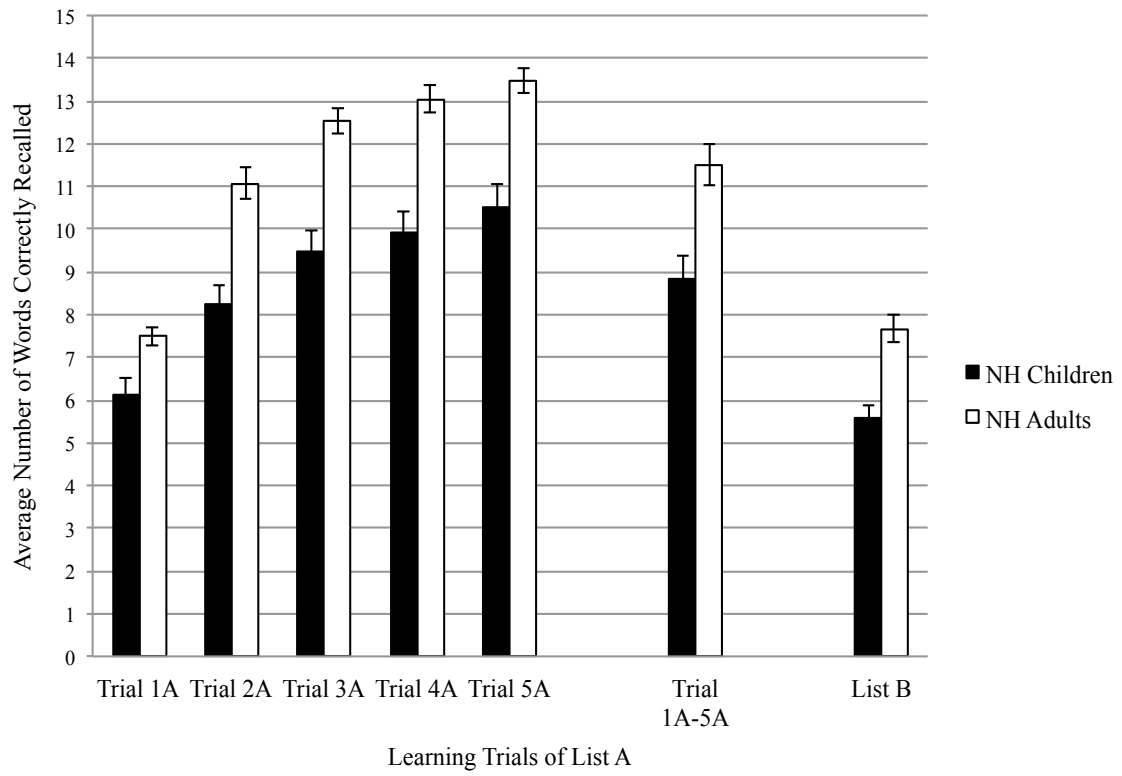


Figure 4.2

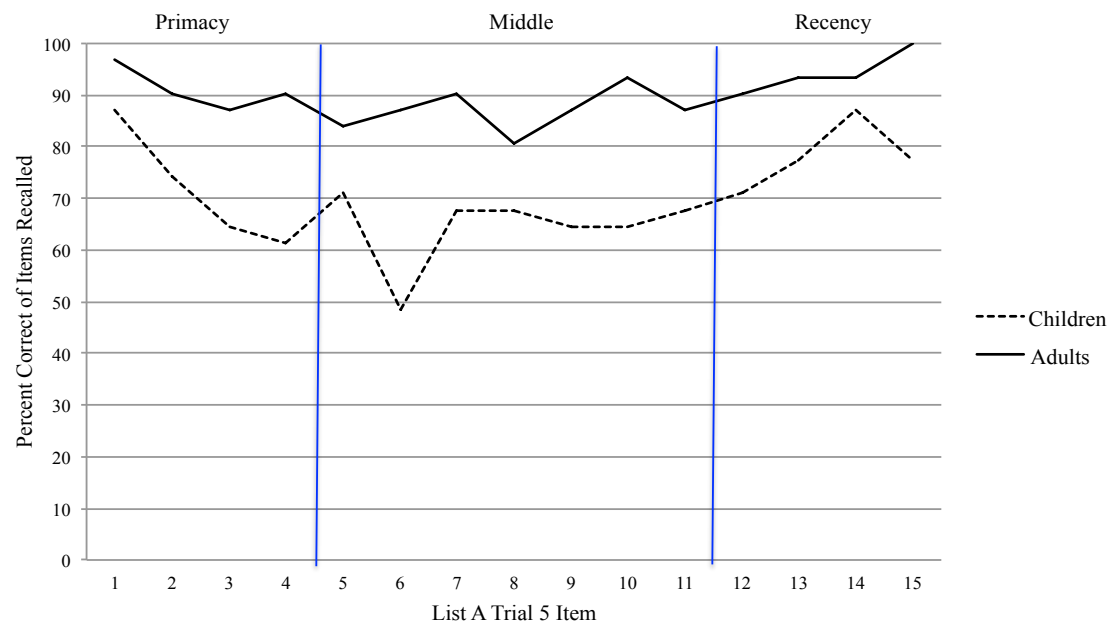
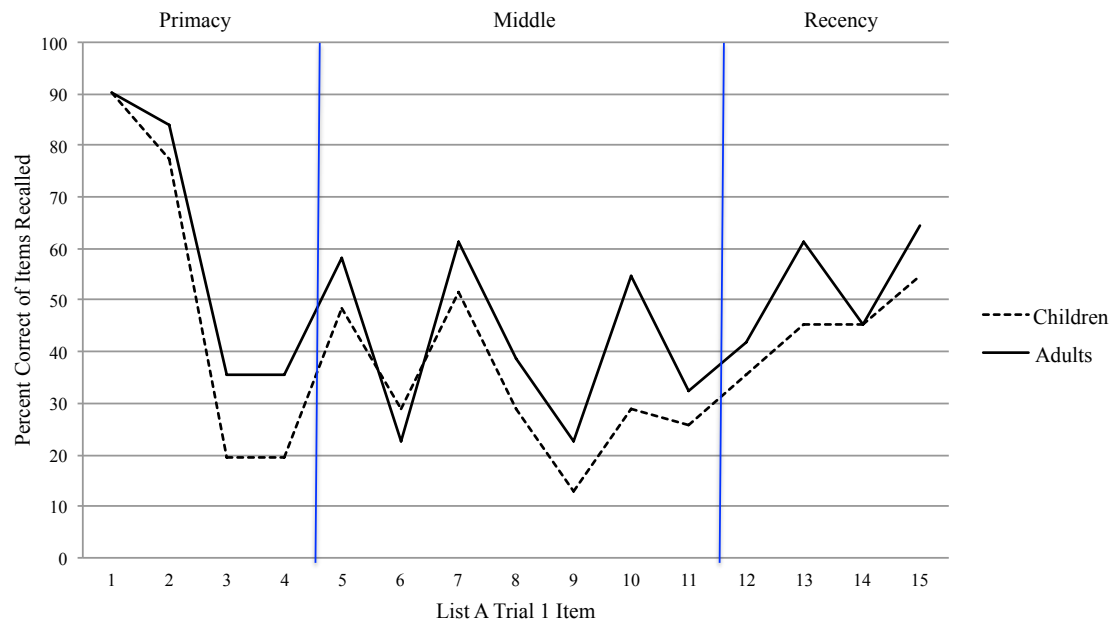


Figure 4.3

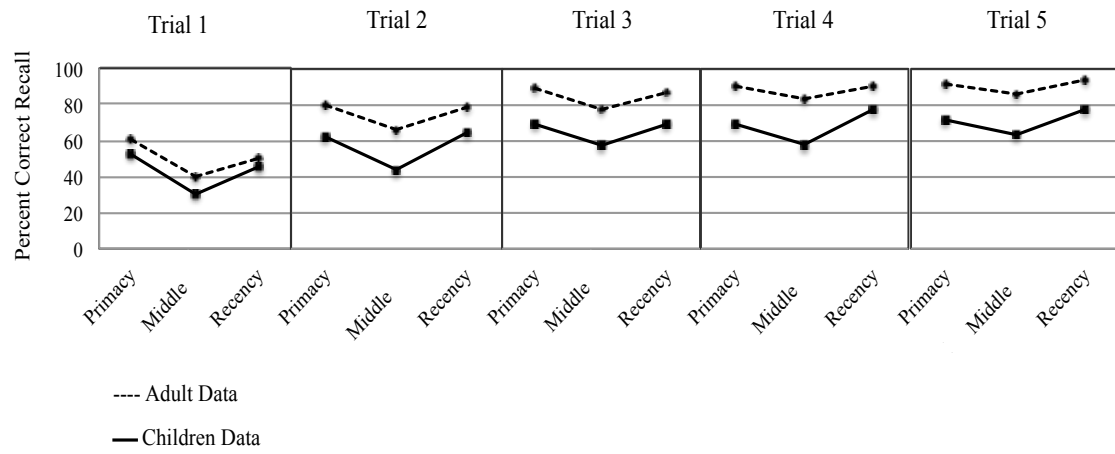


Figure 4.4

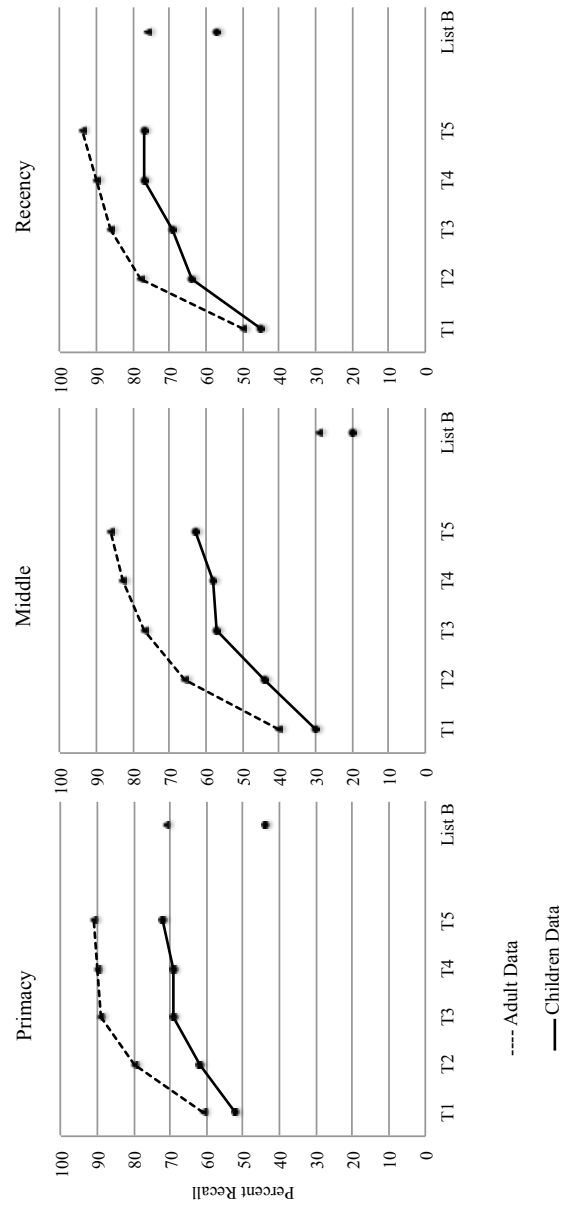


Figure 4.5

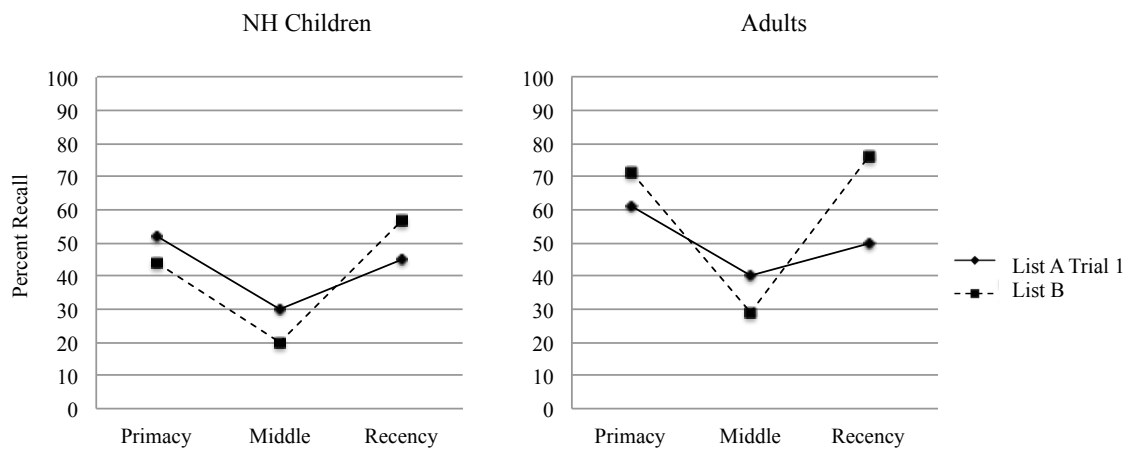


Figure 4.6

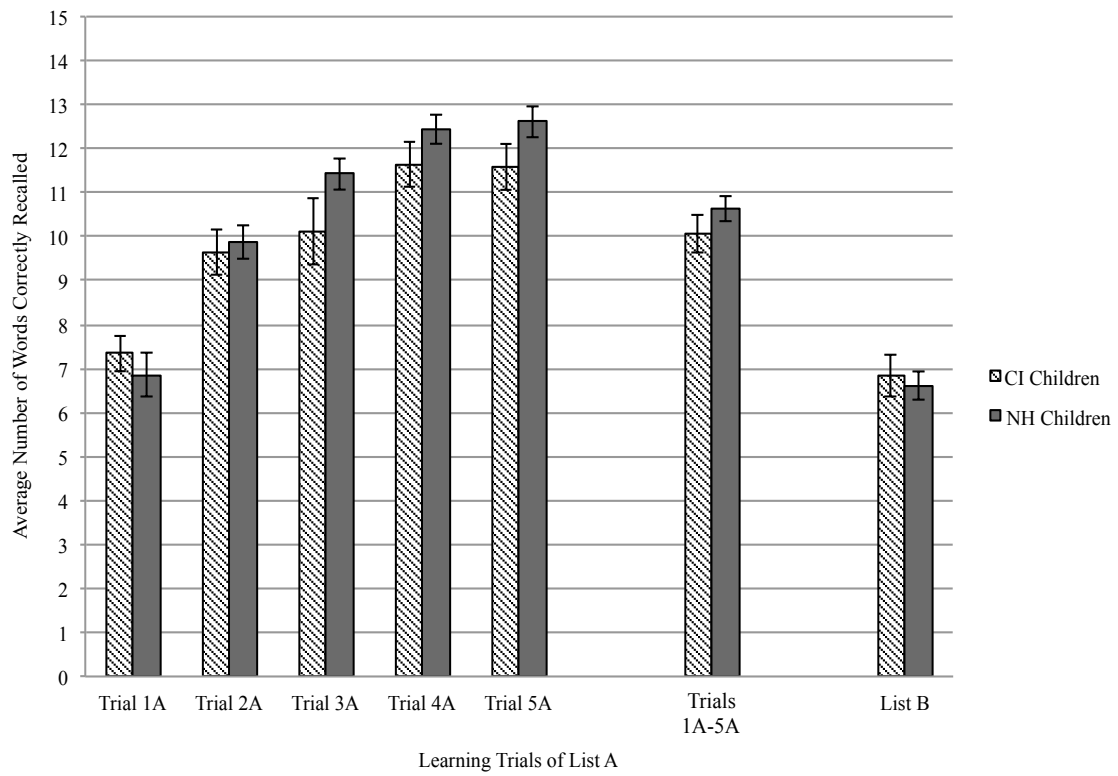


Figure 4.7

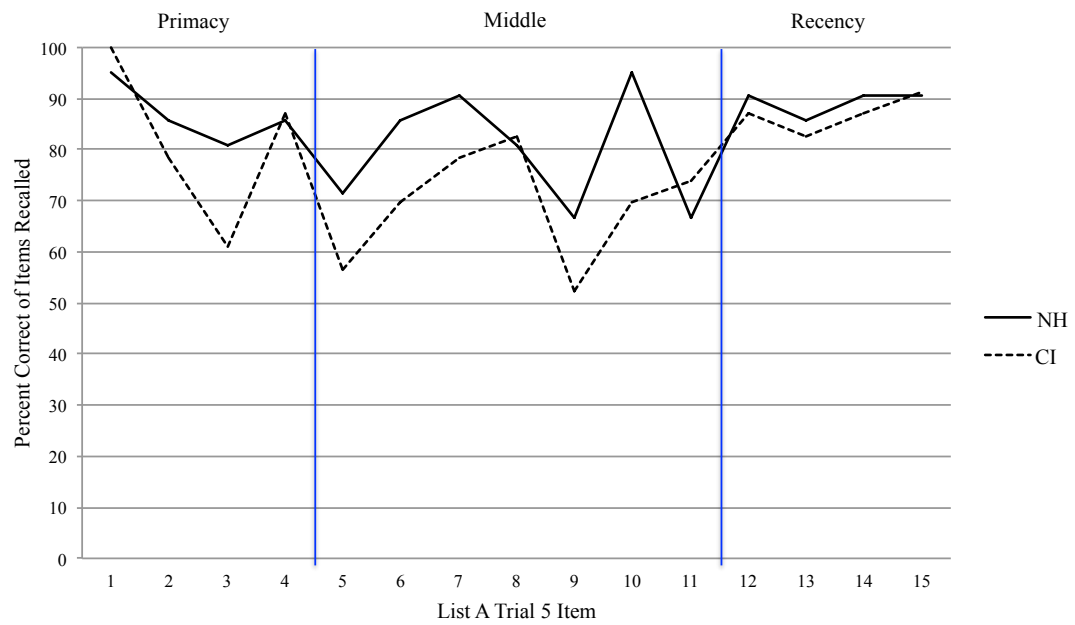
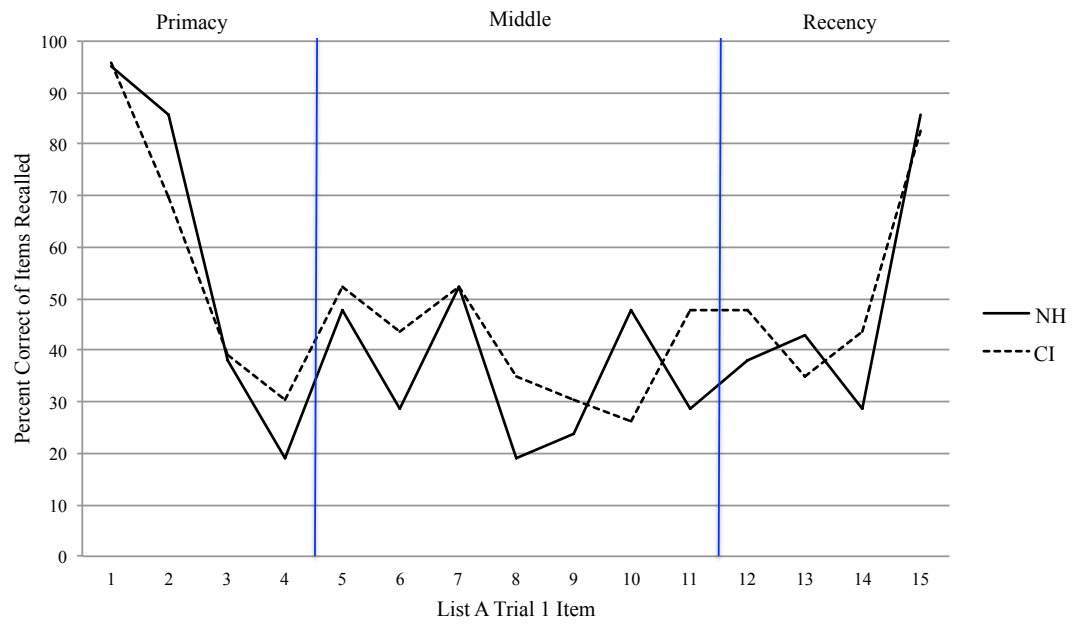


Figure 4.8

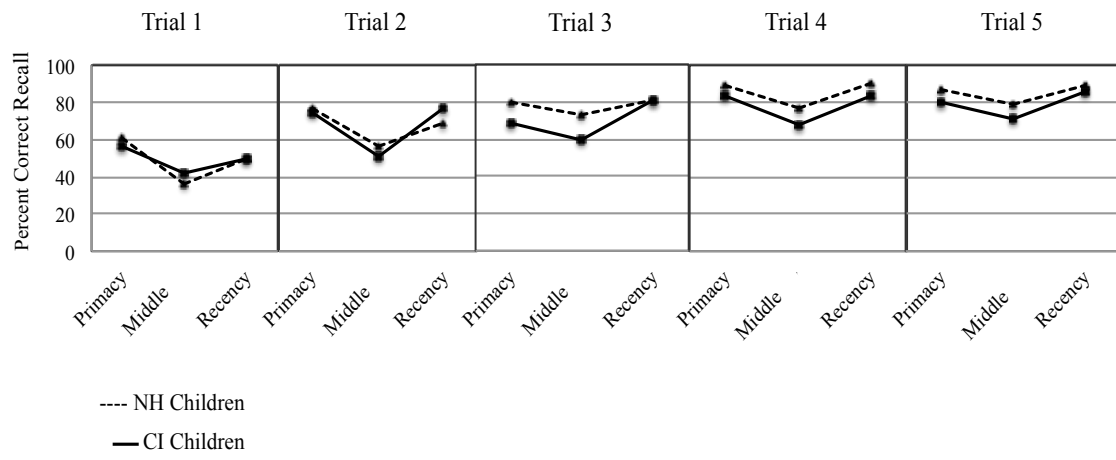


Figure 4.9

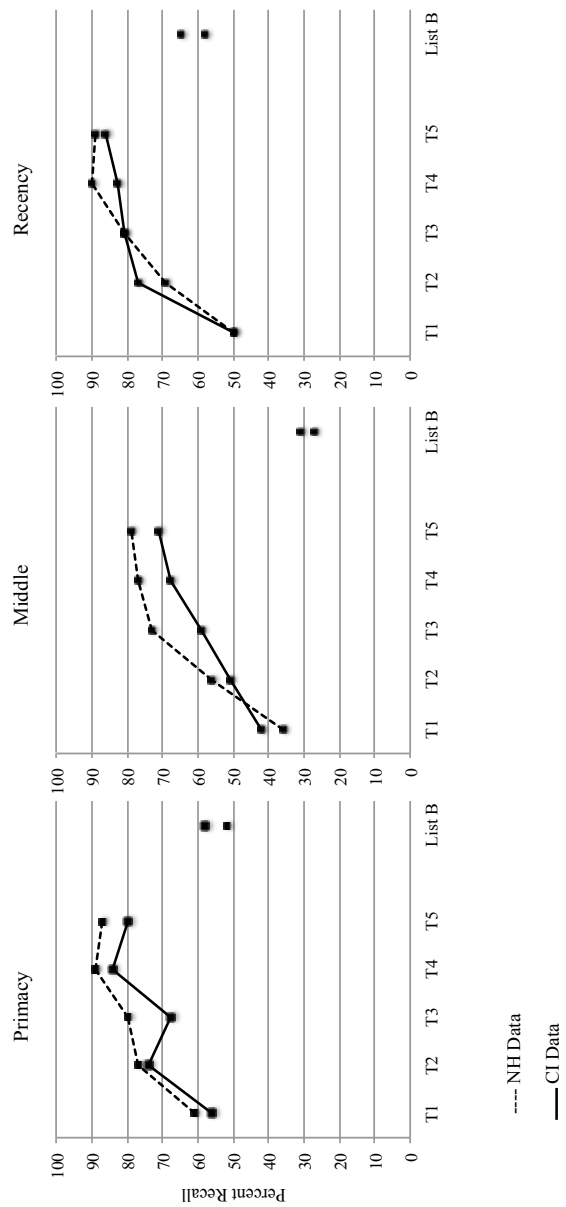
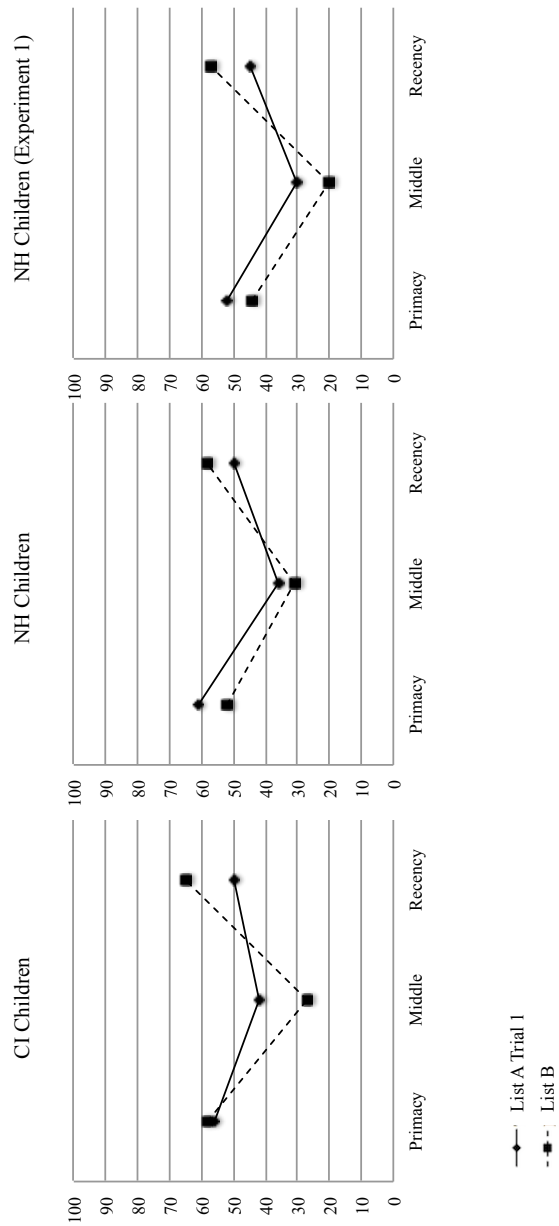


Figure 4.10



CHAPTER 5

SUMMARY AND CONCLUSIONS

“Hearing loss is primarily a brain issue, not an ear issue.”

(Flexer, 2011, p. S19)

The research reported in this dissertation was carried out to investigate the contribution of several core neurocognitive factors in speech perception when degraded and underspecified phonological and lexical representations of speech are presented to listeners. More specifically, we wanted to understand the contribution of auditory attention, short-term memory, and verbal learning and memory to vocoded speech perception in normal-hearing (NH) children. This research was motivated in part by the seminal study by Eisenberg, Martinez, Holowecky, and Pogorelsky (2002) who first used vocoded speech with NH children to evaluate performance on lexically controlled speech recognition tasks while varying the amounts of spectral information available in the signal. While the authors did not extend the research methods to include any cognitive testing, the authors did suggest that variability observed in performance during degraded word recognition tasks was very likely a result of differences in processing abilities of verbal information in short-term memory. Although it has been over ten years since this study was first published, no one has followed-up the study to investigate the authors’ suggestions about the important role of cognition and verbal learning in the perception of degraded speech.

Since Eisenberg et al. (2002), numerous studies have used vocoded speech to investigate the effects of reduced spectral information on speech perception in NH children in hopes of better understanding the processing of speech by hearing-impaired children who have received cochlear implants (CIs) (Conway, Walk, Deocampo, Anaya, & Pisoni, in press; Dorman, Loizou, Kemp, & Kirk, 2000; Maidment, Kang, Stewart, & Amitay, 2014; Newman & Chatterjee, 2013; Vongpaisal, Trehub, Schellenberg, & van Lieshout, 2012; Warner-Czyz, Houston, & Hynan, 2014). The use of spectrally-degraded vocoded speech is an important and very valuable research tool because it allows researchers to investigate factors influencing speech perception processes under challenging conditions and to replicate the hearing experience produced by CIs in NH children who have typically-developed cognitive systems. While the previously mentioned studies have provided additional new knowledge and understanding of the perceptual processing and requirements for NH listeners to successfully perceive degraded speech, the involvement of cognition has largely been neglected. The exclusion of tests to assess cognitive information processing abilities under these vocoded conditions is a serious problem because previous research with CI children has shown that speech perception is a multisensory process that is closely linked with numerous aspects of cognition (Beer, Kronenberger, & Pisoni, 2011; Burkholder & Pisoni, 2003; Cleary, Pisoni, & Kirk, 2000; Harris et al., 2013; Kronenberger, Pisoni, Henning, & Colson, 2013).

The first goal of the present research was to carry out a replication of Experiment 2 from Eisenberg et al. (2002) to assess the robustness of the original findings that demonstrated the influence of word frequency and neighborhood density on the

recognition of vocoded speech by NH children. We also extended the replication by including a group of NH young adults to serve as a benchmark comparison group. We carried out additional analyses examining context benefit from words in sentences, added an expressive vocabulary assessment, and also investigated whether perceptual learning occurred during the two vocoded speech recognition tasks.

As described in Chapter 2, we successfully replicated the main findings from the Eisenberg et al. (2002) study by showing that both NH children and adults recognized lexically easy words better than lexically hard words in both isolation and in sentences and that accuracy for words in sentences was better than for the same words presented in isolation. Successfully replicating the Eisenberg et al. (2002) study was critical to this research because if the familiarity and distinctiveness of a word affects recognition, then it strongly supports the suggestion for involvement of cognition in degraded speech perception and not just a reliance on quality of acoustic information available in the speech signal. This replication was the motivation for the rest of the dissertation and was the logical prerequisite for any new research studies that make use of Eisenberg et al.'s (2002) original stimuli and methodology. Additional analyses examining context benefit gain using speech perception data from Eisenberg et al.'s (2002) original study and the current study also showed that children with CIs were unable to use context efficiently to aid them in spoken word recognition when compared to NH children listening to vocoded speech. This is another finding that provides support for the important contribution of cognitive functioning and abilities on speech perception. We also found that expressive vocabulary scores showed stronger relations with vocoded speech perception abilities compared to receptive vocabulary scores. Thus, children who encode words with

stronger memory traces needed for expressive recall are also those children who performed better on degraded speech recognition tasks. Lastly, perceptual learning of degraded vocoded speech appeared to take place in NH children and adults in a relatively short period of time suggesting that rapid adaptation and adjustment are fundamental information processing skills that might promote robust speech recognition in challenging listening conditions.

The second goal of this research was to investigate the effects of neurocognitive functioning on the perception of degraded speech. Specifically, we assessed relations between vocoded sentence perception and measures of auditory attention (NEPSY Auditory Attention and Response Set and a talker discrimination task) and short-term memory (visual digit and symbol spans) in NH children. We chose auditory attention and short-term memory as our measures of cognition because previous research has shown these to be significant cognitive outcome measures related to spoken language development in children with CIs, who must process degraded speech as a result of limitations of the CI device (Cleary & Pisoni, 2002; Cleary, Pisoni, & Kirk, 2005; Dawson, Busby, McKay, & Clark, 2002; Eisenberg et al., 2002; Pisoni & Geers, 2000).

As described in Chapter 3, analyses revealed significant relations between performance on the neurocognitive measures and vocoded sentence perception task. One unexpected finding was that only one of the measures of auditory attention (the talker discrimination task) was related to how well a child perceived vocoded sentences. Neither of the two NEPSY-2 subtests was found to be correlated with performance on vocoded speech recognition. One explanation of this finding is that both the Auditory Attention and Response Set tasks were too easy and performance was close to ceiling.

However, both conditions of the talker discrimination task- a measure of the listener's ability to attend to indexical properties of speech- were significantly correlated with vocoded speech recognition. Additionally, because both the talker discrimination task and sentence perception task were presented under vocoded conditions, the relations found between the two measures may also be interpreted as reflecting individual differences in how well the children could process vocoded speech and control their attention to components of the speech signal. Children who are better at perceiving vocoded speech would have an advantage on tasks using vocoded stimuli, such as the talker discrimination task. Of special interest were the significant relations between both the visual digit and symbol short-term memory span measures and performance on the vocoded sentence recognition task. These specific findings suggest that cognitive abilities supporting degraded speech perception are not modality-specific; that is, the cognitive abilities involved in perceiving speech may not be limited to the auditory domain and audibility of the signal.

The findings from Chapter 3 support the proposal that vocoded speech perception not only reflects only peripheral auditory processes, but also the contribution of more central cognitive processes as well. The findings also suggest that auditory attention and short-term memory support spoken word recognition when there are suboptimal listening conditions present. These findings are pertinent to populations of hearing-impaired listeners, who regularly receive transformed and impoverished acoustic signals and must activate compensatory cognitive strategies to maximize speech perception performance. Knowing specific cognitive factors that are related to performance on degraded speech perception and spoken word recognition can not only help in identifying children who

may be at high risk for developing delays in speech and language but may also help with developing novel targeted interventions to increase cognitive processing abilities that underlie speech perception and spoken language processing.

Lastly, we used the California Verbal Learning Test – Children’s Edition (CVLT-C) to investigate verbal learning and memory in NH and CI children and to assess the relations between the perception of spectrally-degraded speech and several core foundational verbal learning and memory processes. The CVLT-C is a “high-yield” standardized neuropsychological assessment instrument that uses a multi-trial free recall task. Using the CVLT-C to study basic verbal learning and memory provided us with a unique opportunity to examine patterns of learning and memory within- and between-groups and assess how these measures relate to degraded speech recognition abilities. Experiment 1 investigated relations between verbal learning and memory and vocoded speech perception in NH children and adults. Experiment 2 investigated relations between verbal learning and memory and speech perception in a group of children with CIs and age-matched NH controls. In addition to examining measures obtained from the CVLT-C scoring program, we decomposed recall performance for each test list into three serial curve subcomponents: recency, middle, and primacy. This procedure allowed us to uncover and investigate patterns of learning and memory that were masked by the original scoring program which summed over all the individual learning trials and serial positions in the test lists.

As described in Chapter 4, many novel significant findings were uncovered about how CI and NH children encode, store and retrieve verbally presented sequential information. First, the results indicated that listeners who performed better on the speech

perception tests demonstrated greater recall of information and a faster learning rate than listeners who did poorly on these tests. Thus, stronger speech perception skills were related to better verbal learning and memory. Secondly, we found significant differences in verbal learning strategies based on the serial position of words in the list. The ability of NH listeners to recall test items from the earlier portions of the list was significantly related to performance on degraded speech perception measures (Experiment 1) whereas recall from later portions of the list was significantly related to speech perception measures for the CI children (Experiment 2). Additionally, we found that both NH children and adults who used serial recall strategies (serial clustering) were better at recognizing vocoded speech, a finding that was not observed in the CI children's data. Therefore, it appears that children with CIs may rely more heavily on recency memory because they have less efficient verbal rehearsal and organizational strategies (serial recall) to help them transfer spoken words from short-term memory into long-term memory in a short period of time during the multi-trial free recall task.

Taken together, the results obtained from these three studies provide additional support and new evidence for the involvement of cognitive factors- specifically, auditory attention, short-term memory, and verbal memory and learning- in the perception of vocoded speech by NH children. It is also likely that this relationship between neurocognitive functioning and vocoded speech perception is bidirectional where speech perception abilities support neurocognitive functioning. Because these analyses are correlational in nature, it is not possible to determine the direction or degree of causality, but we would be remiss to not acknowledge the likely reciprocal nature between speech perception and neurocognitive functioning.

The research findings from these studies are theoretically significant because they represent the first investigations to explore relations between neurocognitive performance in typically-developing NH children and their ability to perceive vocoded speech using degraded signals that yield underspecified phonological and lexical representations. Since we held the amount of spectral information presented to all of the NH children constant (all received 4-channel simulations), the variability in outcome performance demonstrates that underlying cognitive abilities are being utilized as compensation for the reduced and degraded acoustic information in the signal. As a result, this research contributes to basic cognitive and speech perception sciences in many ways. Children rarely encounter environments absent of competing sounds or distractions so simulating an environment where information is “lost” in the signal can help us understand what cognitive processes compensate for the reduced information in the signal. Also, using spectrally-degraded speech allowed us the unique opportunity to learn about relations between neurocognitive functioning and degraded speech perception that are relevant to clinical populations with hearing impairment without needing to control for factors related to hearing loss.

Currently, the overwhelming majority of research in vocoded speech perception has focused on the amount of spectral information in the signal needed by a NH listener to perceive vocoded speech. While this is important fundamental knowledge for understanding perceptual processing of speech, it does not fully explain the variability observed in performance by both NH and CI children. Findings from the current research in which the audibility of the speech signal was held constant suggest that some additional sources of variability in performance outcome measures reflect individual

differences and variability in basic cognitive abilities. Knowing the neurocognitive processes that support perception of degraded speech is critical for developing much needed targeted interventions, especially for hearing impaired children with CIs who may not be performing optimally. For children with CIs, the primary focus of many clinicians is to increase the quantity and quality of acoustic input transmitted through the CI. However, when options become limited for improving the perceptual input, other avenues for intervention need to be explored. If researchers and clinicians knew more about the specific neurocognitive factors that underlie degraded speech perception, novel interventions targeting those relevant neurocognitive factors could be tailored to produce downstream improvements in speech perception under challenging conditions. Although this research only explored a few areas of neurocognitive processing that contribute to the perception of degraded speech, it has established the need for extending future research in hearing impaired children with CIs to include new measures of cognition such as controlled attention, verbal learning, and memory. The research studies reported here adopted a “whole systems approach” by incorporating both perceptual and cognitive measures in an attempt to explain variability in performance and will motivate future research to follow the same approach.

There are several limitations to this research that should be acknowledged and considered when interpreting the results. First, because the NH children and adults were only acutely exposed to vocoded speech, analyses investigating the neurocognitive processes that support vocoded speech reflect this brief exposure to degraded speech signals. The NH listeners also showed evidence of rapid perceptual learning, something we did not control for and should consider for future studies. Lastly, we used small

groups of listeners and the research studies consisted largely of correlational analyses. The correlational analyses presented in this dissertation provided valuable new insights into some of the basic foundational neurocognitive processes related to vocoded speech perception, but it is important to recognize that correlation does not equal causation. Future research should use larger samples and carry out specific experimental manipulations of variables (e.g. manipulating cognitive load or amount of spectral degradation) to test hypotheses about the underlying processing operations.

This research provides motivation and a foundation for the continued use of vocoded speech in investigating ties between neurocognitive functioning and degraded speech perception. Future research should investigate neurocognitive processes related to other types of speech degradation. It would be important to know if the cognitive processes involved are specific to certain types of noise or degradation. Also, presenting the CVLT-C visually, eliminating issues of audibility entirely, would be beneficial for use with hearing impaired populations because it would reduce possible confounds related to the quality of the initial sensory and perceptual input received by the listener.

In summary, the findings reported in the three studies in this dissertation represent some of the first attempts to uncover the core information processing mechanisms used in the perception of vocoded spectrally-degraded speech in young children. The use of vocoded spectrally-degraded speech has become an important research tool to study speech perception and spoken language processing in NH populations using a simulation of the acoustic output of a CI. Human speech perception and spoken language processing is extremely robust over a wide range of listening conditions. It is now becoming clear that robust performance reflects the operation of the entire information

processing system working together as a functionally integrated system. While audibility and early sensory processing and encoding of speech and other complex signals play an important role in the initial registration of auditory signals by the brain and nervous system, the contribution of the rest of the system and the interactions among components of the system can no longer be ignored and relegated to the side lines. As Ronnberg and his colleagues have stated recently--“Cognition Counts” --and it is time that these central components of the language comprehension system are fully acknowledged and studied alongside the early sensory processing by the auditory periphery (Rönnberg, Rudner, Foo, & Lunner, 2008).

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Appendix A

Eisenberg's Lexically Controlled Test Words			
"Easy" Words		"Hard" Words	
1. Kind	31. Please	1. Tell	31. Knows
2. Airplane	32. Help	2. Sleep	32. Leave
3. Brown	33. Puzzle	3. Belly	33. Money
4. Stand	34. Don't	4. Bunny	34. Piggy
5. Broken	35. Scribble	5. Hid	35. Moved
6. Truck	36. Door	6. Room	36. Books
7. Children	37. Seven	7. Likes	37. Gum
8. Cried	38. Eggs	8. Share	38. Tiny
9. Farm	39. Street	9. Butter	39. Box
10. Broke	40. Just	10. Son	40. Tummy
11. Finger	41. Grey	11. Played	41. Ten
12. School	42. Shoelace	12. Chickens	42. Days
13. Friend	43. Wonder	13. Ever	43. Start
14. Thinks	44. Brought	14. Find	44. Walking
15. Lipstick	45. Food	15. Toys	45. Seat
16. Give	46. Which	16. Grampa	46. Taught
17. Monkey	47. Space	17. Laughed	47. Us
18. Juice	48. Black	18. Goats	48. Trick
19. Wash	49. Its	19. Dad	49. Worm
20. Ducks	50. Watch	20. Came	50. Stuck
21. Myself	51. Fish	21. Hello	51. Pool
22. Draw	52. Lets	22. Boys	52. Guess
23. Little	53. Gas	23. Turns	53. Were
24. Snake	54. From	24. Locking	54. Rain
25. Open	55. Girl	25. Many	55. Cups
26. Green	56. Takes	26. Kids	56. Pink
27. First	57. Milk	27. Learn	57. Bag
28. String	58. Break	28. Lost	58. Both
29. Stay	59. When	29. Mommy's	59. Cats
30. Pocket	60. Jump	30. Ring	60. Mine

Appendix B

Eisenberg's Lexically Controlled Test Sentences	
“Easy” Sentences	“Hard” Sentences
1. That kind of airplane is brown.	1. Tell him to sleep on his belly.
2. You can't stand on your broken truck.	2. The bunny hid in my room.
3. The children cried at the farm.	3. She likes to share the butter.
4. I broke my finger at school.	4. His son played with the chickens.
5. My friend thinks her lipstick is cool.	5. Call if you ever find the toys.
6. Give the monkey some juice.	6. Grampa laughed at the goats.
7. I can wash the ducks myself.	7. Dad came to say hello.
8. I can draw a little snake.	8. The boys took turns locking the car.
9. Open the green one first.	9. Many kids can learn to sing.
10. The string can stay in my pocket.	10. She lost her mommy's ring.
11. Please help her with the puzzle.	11. She knows where to leave the money.
12. Don't scribble on the door.	12. The piggy moved the books.
13. I saw seven eggs in the street.	13. The gum is in the tiny box.
14. I just found the grey shoelace.	14. His tummy hurt for ten days.
15. I wonder who brought the food.	15. Start walking to your seat.
16. I know which space is black.	16. He taught us that funny trick.
17. Its always fun to watch the fish.	17. The worm was stuck in the pool.
18. Lets buy gas from that man.	18. I guess you were in the rain.
19. I hope the girl takes some milk.	19. The cups are in the pink bag.
20. The chair could break when I jump.	20. Both of the naughty cats are mine.

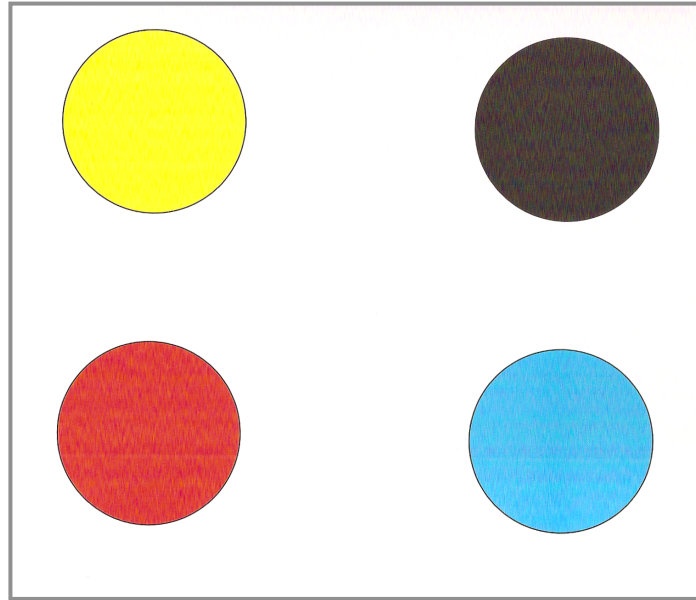
Appendix C

Example response sheet from WIPI assessment



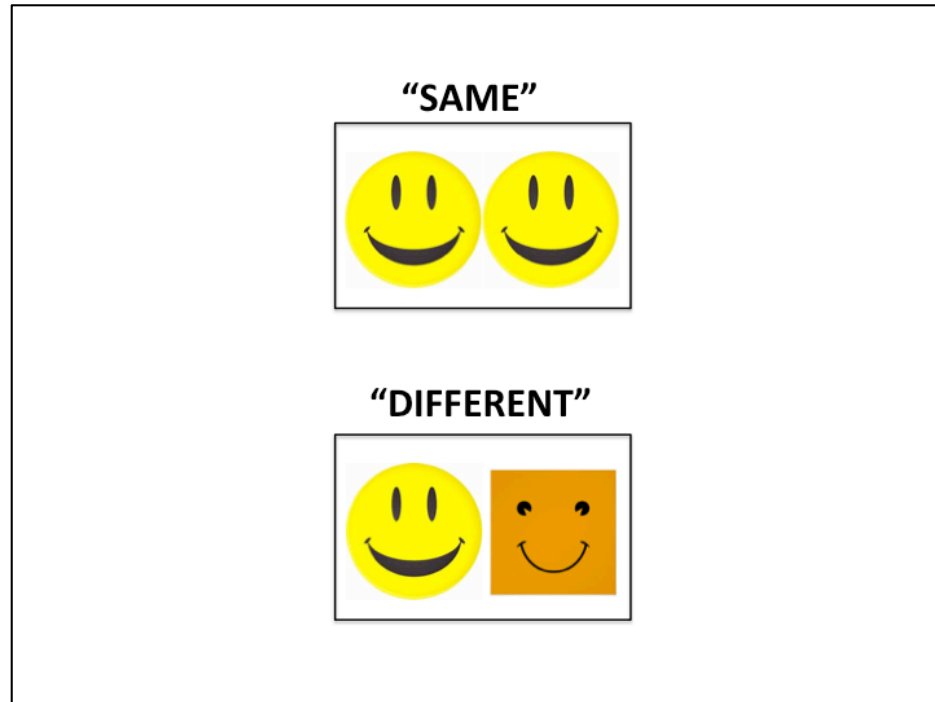
Appendix D

NEPSY Auditory Attention and Response Set response sheet



Appendix E

Response screen for Talker Discrimination task.

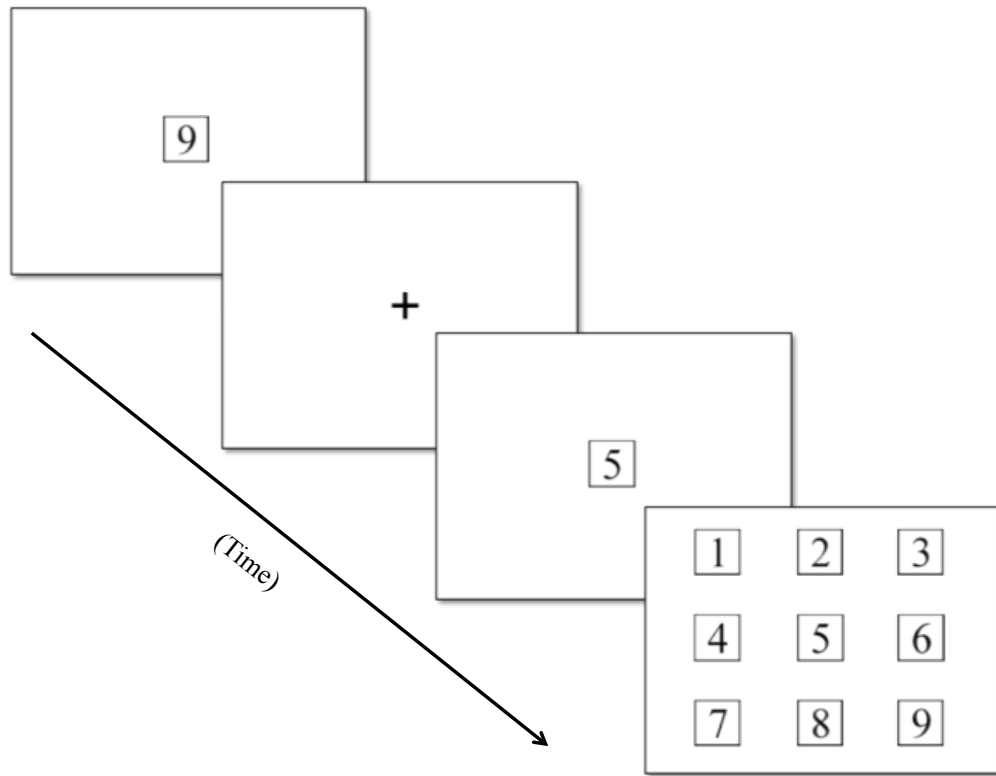


Appendix F

Sentence Pairings for Talker Discrimination Task	
Fixed-Sentence Condition	
<i>Sentence 1</i> The juice of lemons makes fine punch.	<i>Sentence 2</i> The juice of lemons makes fine punch.
Varied-Sentence Condition	
<i>Sentence 1</i> A wisp of cloud hung in the blue air. A wisp of cloud hung in the blue air. The horn of the car woke the sleeping cop. The box was thrown beside the parked truck. The two met while playing on the sand. A pound of sugar costs more than eggs. The crooked maze failed to fool the mouse. The ink stain dried on the finished page. The lazy cow lay in the cool grass. The frosty air passed through the coat. The boy was there when the sun rose. The wagon moved on well-oiled wheels.	<i>Sentence 2</i> The pearl was worn in a thin silver ring. The small pup gnawed a hole in the sock. The juice of lemons makes fine punch. The set of china hit the floor with a crash. The wide road shimmered in the hot sun. The ship was torn apart on the sharp reef. The salt breeze came across from the sea. The colt reared and threw the tall rider. The fruit peel was cut in thick slices. The meal was cooked before the bell rang. The hat brim was wide and too droopy. The soft cushion broke the man's fall.

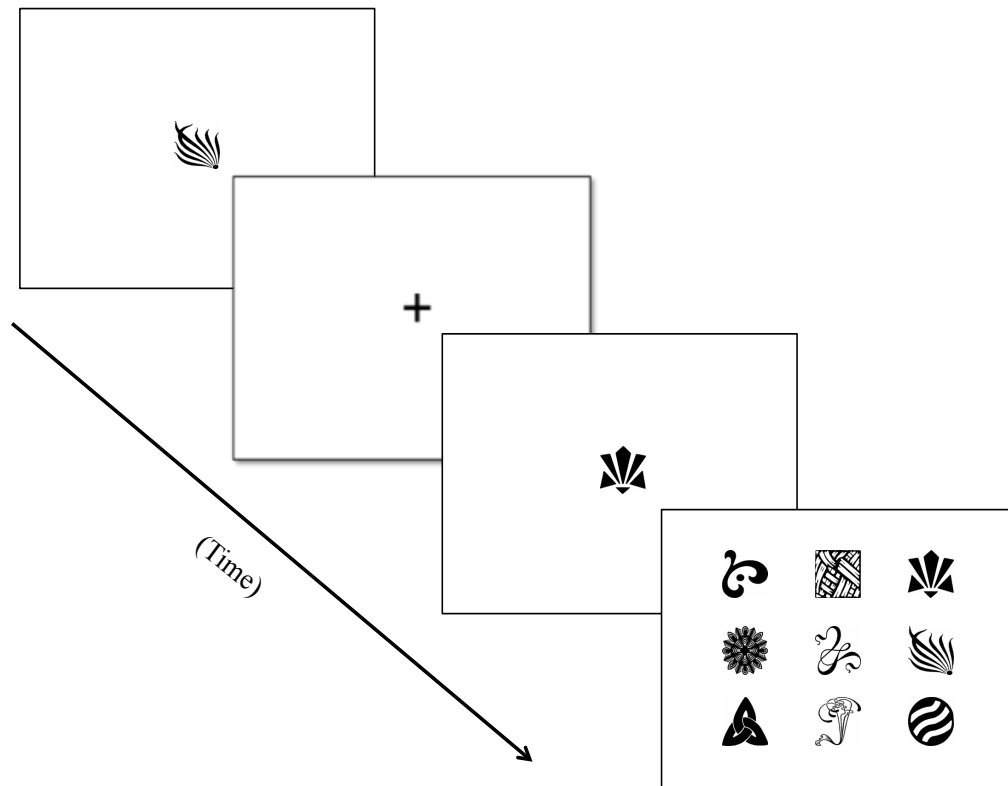
Appendix G

Example sequence (set size of 2) of forward visual digit span task



Appendix H

Example sequence (set size of 2) of forward visual symbol span task



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EDUCATION

Ph.D. (Aug. 2008- Feb. 2015)
Indiana University, Psychological and Brain Sciences
Area: Cognitive Psychology
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Doctoral Dissertation: Neurocognitive Correlates of Spectrally-Degraded Speech Recognition in Children
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B.A. (Aug. 2003- Dec. 2006)
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Area: Psychology with a concentration in Natural Sciences
Honor's Thesis: *The Relationship Between Perseveration and Aggression with Consideration to Sex Differences*.
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RESEARCH EXPERIENCE

Graduate Research Fellow, June 2008- Jan. 2015
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Research Analyst (Full-Time), Jan 2007-June 2008
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"Sleep and Psychophysiological Functioning in Children" (NHLB 5R01HL070911) awarded to Dennis Molfese, Ph.D., Developmental Neuropsychology Laboratory, Department of Psychological and Brain Sciences, University of Louisville

Research Assistant, Jan 2007-Apr 2007
Early Childhood Research Center- Victoria Molfese, Ph.D., Department of Education, University of Louisville

Undergraduate Research Assistant, Aug. 2005 - Apr. 2006
Schizophrenia Research Laboratory of Richard Lewine, Ph.D., Department of Psychological and Brain Sciences, University of Louisville

PUBLICATIONS

- Nelson, T.D., Lundahl, A., Molfese, D.L., Waford, R., **Roman, A.**, Gozal, D., Molfese, V.J., Rue, A., & Ferguson, M. (2014). Estimating child sleep from parent report of time in bed: development and evaluation of adjustment approaches. *Journal of Pediatric Psychology*, 39(6), 624-632.
- Roman, A. S.**, Pisoni, D.B., & Kronenberger, W.G. (2014). Assessment of working memory capacity in preschool children using the missing scan task. *Infant and Child Development*, 23(6), 575-587.
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PRESENTATIONS

- Roman, A. S.**, Pisoni, D. B., & Kronenberger, W. G. (2014, December). *Neurocognitive correlates of spectrally-degraded speech recognition in normal-hearing children*. Paper presented at 14th Symposium on Cochlear Implants in Children, Nashville, TN.
- Faulkner, K, **Roman, A. S.**, Kronenberger, W. G., & Pisoni, D. B. (2014, December). *Verbal learning and memory processes in early-implanted long-term cochlear implant users*. Paper presented at 14th Symposium on Cochlear Implants in Children, Nashville, TN.
- Roman, A. S.** & Pisoni, D. B. (2012, June). *Some preliminary findings using the missing scan task to measure working memory capacity in young children*. Paper presented at the Beyond Newborn Hearing Screening: Infant and Childhood Hearing in Science and Clinical Practice, Cernobbio, Italy.
- Roman, A. S.** & Pisoni, D. B. (2011, July). *Assessment of working memory capacity in young children using a modified version of Buschke's 'missing scan' task*. Poster session presented at the 5th International Conference on Memory, York, England.
- Roman, A. S.** & Pisoni, D. B. (2011, July). *The 'missing scan task' as a new measure of working memory: Preliminary data*. Poster session presented at the 13th symposium on Cochlear Implants in Children, Chicago, IL.
- Harrell, A., Dudley, A., **Roman, A.**, Pratt, N., Molfese, V., & Molfese, D. (2011, February). *Impact of minor sleep loss on speech perception in 6 year-old children: electrophysiological effects*. Poster session presented at the 39th annual meeting of the International Neuropsychological Society, Boston, MA.
- Dudley, A., Harrell, A. **Roman, A.**, Pratt, N., Molfese, V., & Molfese, D. (2011, February). *One-hour per night sleep loss impacts hemisphere processing in 6 year-old children: electrophysiological correlates*. Poster session presented at the 39th annual meeting of the International Neuropsychological Society, Boston, MA.
- Roman, A. S.**, Pisoni, D. B., Kronenberger, W., Geers, A., & Tobey, E. (2010, June). *Measures of memory span and verbal rehearsal speed in deaf children after 8 years of cochlear implant use*. Paper presented at 11th International Conference on Cochlear Implants and Other Auditory Implantable Technologies. Stockholm, Sweden.
- Pisoni, D. B., Kronenberger, W. G., **Roman, A.S.** (2009, June), *Development of immediate*

memory capacity in deaf children with cochlear implants: Digit spans at 8 and 16 years of age. Paper presented at 12th Symposium on Cochlear Implants in Children. Seattle, WA.

Roman, A. S., Warren, C. G., Kheirandish-Gozal, L., Molfese, V. J., & Molfese, D.L. (2008, August). *Sleep restriction and recovery on speech discrimination in adults.* Poster session presented at American Psychological Association Convention. Boston, MA.

Roman, A. S., Pratt, N. L., Dayyat, E., Gozal, D., Molfese, V. J., Molfese, D. L. (2008, June). *Using electrophysiology to better predict minor sleep loss in children.* Poster session presented at the 22nd Annual meeting of the Associated Professional Sleep Societies (APSS). Baltimore, MD.

Dayyat E., Spruyt K., **Roman A.**, Molfese D. L., Gozal D. (2008, June). *Recovery from 1-week mild sleep restriction in 4-8 year-old healthy children.* Poster session presented at the 22nd Annual meeting of the Associated Professional Sleep Societies (APSS). Baltimore, MD.

Kang, Y., **Roman, A.**, Gozal, D., Molfese, V. J., & Molfese, D.L. (April, 2008). Impact of true sleep time on the auditory attention of 6 to 8 year old children. Poster session presented at the Conference on Human Development, Indianapolis, IN.

Roman, A., Beswick, J., Molnar, A., Molfese, V., Gozal, D., Molfese, D. (2008, February). *Impact of minor sleep loss on speech perception in 7 year olds.* Poster session presented at the 36th annual meeting of the International Neuropsychological Society, Waikoloa, HI.

Molfese, D. L., Fonaryova Key, A., Rue, A., **Roman, A.** Invited Presentation. (2007, October). *Developmental changes in word learning effects to auditorally named visual stimuli.* Symposium on "How Early Is Semantics? Electrophysiological Correlates Of Semantic Processing Peaking Earlier Than The N400." 47th Annual Meeting of the Society for Psychophysiological Research (SPR), Savannah, GA.

Roman, A. S., Kang, Y. J., Gozal, D., Molfese, V. J., & Molfese, D. L. (2007, October). *Does true sleep time matter? Relationship to auditory attention of 6 to 8 year old children.* Poster session presented at Research! Louisville, Louisville, KY.

Molfese, D. L., Molfese, V. J., Gozal, D., **Roman, A.** Invited Presentation. (2007, June). *Event-related potentials in sleepy preschool and primary children.* Associated Professional Sleep Societies (APSS). Minneapolis, MN.

Molfese, D. L., Waford, R. N., Warren, C., Pratt, N. Barnes, M., **Roman, A.**, Stone, M., Gozal, D., & Molfese, V. Invited Presentation. (2006, November). *Cognitive impact of weightlessness in NASA astronauts.* Kentucky Psychological Association, Louisville, KY.

TEACHING EXPERIENCE

Instructor of Record, Experimental Methods in Psychology- P211, Psychological and Brain Sciences Department, Indiana University, Jan. 2011- May 2011

Teaching Assistant, Human Memory- P460/P560, Psychological and Brain Sciences Department, Indiana University, Instructor: David Pisoni, Ph.D., Sept. 2009- May. 2012

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- Memory Development in Childhood in Human Memory course, David Pisoni, Ph.D., (Fall 2010; Fall 2011; Spring 2012, Fall 2012, Spring 2013)
- Executive Functioning: Multitasking in Cognitive Psychology course, Tom Gruenenfelder, Ph.D., (Spring 2011)

HONORS AND AWARDS

NIH Fellowship, Pre-Doctoral Trainee, NIH-NIDCD Training Grant T32-DC00012, 2008-present

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COLLEGIATE HONORS

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American Psychological Association (student affiliate)	2005 - present
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Reviewer for APSSC RISE Research Award Competition, March 2012.
Paper moderator at the Conference on Human Development, April 2006, Louisville, KY.