January 2011

The Effects of Visuospatial Sequence Training with Children who are Deaf or Hard of Hearing

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THE EFFECTS OF VISUOSPATIAL SEQUENCE TRAINING WITH CHILDREN WHO ARE DEAF OR HARD OF HEARING

by

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A dissertation presented to the
Graduate School of Arts and Sciences
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

May 2011

St. Louis, Missouri

Acknowledgments

Completing a task such as this is not a solitary effort, and I wish to thank the many people who played a part in helping me achieve this goal. First of all I would like to thank all of the parents who allowed their children to participate in this study. Next, of course, I am grateful to all of the children. Without their willingness to pay attention and to work hard through all of the testing and training sessions I could not have completed this study. My gratitude also goes out to the staff and administration at Immaculate Conception School, Central Institute for the Deaf, and the Moog Center for Deaf Education for their cooperation and flexibility in coordinating times and locations for me to conduct my study.

I express sincere gratitude to Dr. William Clark, my advisor and committee chair, who has been a source of encouragement to me over the course of my career. His guidance and support made it possible for me to venture out into a new and exciting area of study with children who are deaf or hard of hearing. I am grateful to Dr. Rosalie Uchanski who listened to my interests during my qualifying exams and pointed me in a direction aligned with those interests. It was her foresight that led me to meet and ultimately collaborate with Dr. Christopher Conway. It is impossible for me to convey the extent of my gratitude to him. His pursuit of excellence was a source of inspiration, and his patience, advice, and support were a sustaining factor throughout this process.

I am indebted to Dr. Michael Strube for his guidance and untiring patience in helping me with the data analyses. His willingness to answer any question and to offer suggestions with seemingly endless patience is truly appreciated.

I would also like to thank my coworkers at Central Institute for the Deaf who provided encouragement throughout this process. A special thank you goes to Andrea Osman for being such a great listener and for providing a positive perspective whenever I felt overwhelmed.

A final word of thanks goes to my family. My sons Alex, Adam, Austin, and Aaron have played a large part in this long journey, providing me with love and support each step of the way. I want to thank them for their enthusiasm as I worked to earn this degree and for their understanding as I juggled to fulfill my responsibilities as student, full-time employee and mom. I must thank them as well for their technical support as they helped me retrieve "lost" data and work around quirks in software products to configure graphs and tables. Finally I want to thank my husband and best friend, Brian, without whom none of this would have been possible. His belief in me and continued encouragement throughout this journey have allowed me to turn my dreams into reality, and for that I will be forever grateful.

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Abstract

Despite advances in hearing aid and cochlear implant technologies, many children who are deaf or hard of hearing continue to lag behind typically hearing peers in language and reading abilities. Additionally, there is a high degree of variability in language outcomes among children with a hearing loss. Evidence indicates that auditory input provides a foundation not only for speech and language development but for cognitive functions such as sequence memory and learning ability. This study investigated a variety of cognitive functions with two major aims in mind: 1) to verify differences between children who are deaf or hard of hearing and typically hearing children on variety of cognitive tasks, 2) to determine if visuospatial sequencing practice would result in improvements on nontrained tasks measuring phonological memory, sequencing ability, and executive function.

Thirty-two children who were deaf or hard of hearing and 29 children with typical hearing took part in this study. One pretraining and two post training sessions assessed cognitive tasks involving visuospatial short-term memory; verbal short-term memory (nonword repetition); inhibition; and visual sequence learning. Pretraining assessments revealed significant differences between the groups on verbal tasks with both auditory and visual stimuli as well as on tasks of inhibition and visual sequencing. In addition, differences were revealed on visual tasks with nonverbal stimuli. These findings suggest a general difference or delay in performance beyond the anticipated verbal delay related to a deficit in hearing acuity. The training task utilized a touch screen computer monitor that displayed sequences of circles on a 4 x 4 grid which subjects then replicated. Subjects were age matched and completed ten days of visuospatial sequencing practice in either an adaptive or control condition. Two post training assessment sessions revealed improvement on the nonword repetition task for the adaptive group following the sequencing practice. These findings suggest that visuospatial sequencing practice can lead to improvements in language abilities. Possible applications include utilizing measures of visual sequencing ability to identify deaf or hard of hearing children who may be at risk for poorer language development and as a component in predicting successful language development following cochlear implantation.

Chapter I. Introduction

Approximately 1.3 out of 1,000 children in the United States who receive a hearing screening at birth are identified with a hearing loss ("Summary," 2008). Evidence has shown that early stimulation is essential for the normal development of central processes in sensory systems (Sharma & Dorman, 2006). Thus the effects of a hearing loss begin immediately at birth and can continue throughout a child's life. Although the brain and nervous system continue to develop in the absence of auditory stimulation, for children who do not receive adequate auditory stimulation some cortical reorganization does occur leading to differences in both peripheral and central neural function. The resulting effect can be atypical development of speech and language skills (Sharma & Dorman, 2006; Watson, Titterington, Henry, & Toner, 2007) and possibly nonverbal function as well. Therefore it has become a matter of best practice to provide auditory input to children who are deaf or hard of hearing as early as possible.

Hearing aids and cochlear implants are the primary sensory aids provided for children who have been diagnosed with a hearing loss. Both are aimed at restoring the audibility of speech in order to facilitate language development, yet they work in fundamentally different ways. A hearing aid amplifies sound which is then sent to the inner ear and ultimately converted to nerve impulses that are interpreted by the brain. Many hearing aids today utilize programmable digital technology which distinguishes speech from noise and allows the management of loudness. A cochlear implant is a two component device which operates differently than a hearing aid. Rather than simply amplifying acoustic signals, a cochlear implant converts sounds to electrical signals and delivers those signals directly to the auditory nerve. The external component is made up of a microphone, a speech processor, and a transmitter. The microphone picks up sound and sends it to the speech processor. Here sound signals are digitized and sent to the transmitter which then sends the signal to a receiver located internally behind the ear just below the skin. The electrical signals are sent from the receiver to an array of electrodes surgically implanted in the cochlea so that fibers of the auditory nerve can be stimulated. In the final step, nerve impulses are perceived as sound by the brain.

Despite improvements in speech audibility made possible by advances in hearing aid and cochlear implant technologies, many children who are diagnosed with a hearing loss continue to experience difficulty developing verbal communication including speech, vocabulary, grammar, word order, idiomatic expressions, and even reading skills causing them to lag behind their typically hearing peers in these areas (American Speech-Language-Hearing Association, 2011). Additionally, there is a high degree of variability in language and reading abilities among hearing aid and cochlear implant users alike (Blamey, Sarant, Paatsch, Barry, Bow, Wales, Wright, Psarros, Rattigan, & Tooher, 2001; Geers, 2004; Pisoni, 1999). A number of studies have set out to determine factors that may explain the disparity between children with typical hearing and those who are deaf or hard of hearing as well as the variability among this latter group (Dawson, Busby, McKay & Clark, 2002; Geers, Nicholas, & Moog, 2007; Johnson & Goswami, 2010; Pisoni, 1999; Pisoni & Geers, 2000; Willstedt-Svensson, Lofqvist, Almqvist, & Sahlen, 2004). Some of the factors which have been identified include length and degree of auditory deprivation, mode of communication, and nonverbal IQ, yet other more central cognitive factors such as perception, attention, learning, and memory appear to play a role as well. More recent research has suggested that a period of auditory deprivation may cause changes in cognitive processes (Watson et al., 2007). As a result, delays in non-auditory sequencing functions may occur, contributing to difficulties with certain aspects of language development (Conway, Pisoni, & Kronenberger, 2009). Thus there appears to be an additional source of variance related to information processing operations and cognitive demands and which extends beyond audibility and the way in which speech signals are transmitted to the auditory nerve and ultimately encoded into meaningful units (Pisoni, 1999). Evidence suggests that some of these factors may not be fixed traits (Pisoni & Geers. 2000), and recent attention has turned to the possibility of improving various types of cognitive function through the use of computerized training programs (Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlstrom, Gillgberg, Forssberg, & Westerberg, 2005; Kronenberger, Pisoni, Henning, Colson, & Hazzard, 2010).

In the effort to reduce variability in outcomes among children who are deaf or hard of hearing it is essential to understand the impact that a period of auditory deprivation may have on a variety of cognitive functions. If underlying factors related to language and academic performance can be identified and improved then there is potential to increase language skills and to narrow the performance gap between children who are deaf or hard of hearing and their typically hearing peers.

It was therefore the goal of this study first to verify differences between children with typical hearing and those who are deaf or hard of hearing on a variety of cognitive tasks and second to determine whether visuospatial sequencing practice would lead to improvement on these tasks. Before describing the current study and its findings, it is important to review previous research related to the language development of children who are deaf or hard of hearing. This introductory section will define working memory and sequence learning, two factors shown to be related to language development. Studies outlining the contribution of these skills to normal language development will be reviewed. Next, studies describing these skills among children who are deaf or hard of hearing will be presented. Finally, a number of training studies along with the potential to impact language-related skills will be discussed.

Working Memory

The concept of working memory has become important in the study of cognitive function and is generally understood to be the system responsible for temporarily storing information necessary for the performance of complex tasks such as language comprehension (Baddeley, 1992). Working memory generally combines memory, attention, and perception abilities to temporarily store and process information. Short-term storage is facilitated by two slave systems, the phonological loop and the visuospatial sketchpad, and this stored information is acted upon by a set of executive processes which include such things as attention and inhibition, task management, planning, monitoring, and coding representations for time and place of appearance (Smith, 1999). This multi-component concept of working memory has evolved over time and is now widely accepted to describe the processes responsible for a variety of complex cognitive activities, including vocabulary and grammatical development as well as reading comprehension (Adams & Gathercole, 2000; Baddeley, Gathercole & Papagno, 1998; Baddeley, 2003)

Authors of early studies of human memory proposed a unitary system which was responsible for all types of memory, but by the 1950s and 1960s the study of human memory had evolved to suggest a multi-component system for storing information. Atkinson and Shiffron (1968) described the framework of memory as a system divided into a sensory register and a long-term and short-term memory store. According to this view, the presentation of a stimulus activated the sensory register; the long-term memory component served as a durable and lasting repository for information; and a short-term memory component provided a temporary storage space for environmental information. Further investigation and exploration over the years led researchers to create distinctions between this short-term memory store, which maintained information over a limited time period, and the ability to hold that information while manipulating or integrating other information. Thus the terms short-term memory and working memory, while sometimes used interchangeably in the literature, emerged as unique concepts, the latter of which was outlined in the detailed three-component model of Baddeley and Hitch (1974). According to this model, working memory was comprised of two separate systems which temporarily store phonological and visuospatial information as well as a limited capacity attentional system known as the central executive that controls behavior. As further explained, working memory capacity did not solely refer to the quantity of information that could be remembered but also to the ability to control attention in order to maintain or suppress information and as such has sometimes also been referred to as executive attention (Engle, 2002).

The phonological loop, referred to as one of the slave systems and a primary component of Baddeley’s working memory model, is considered to be responsible for maintaining speech-based information. As a highly specialized subsystem it manages both the rehearsal and maintenance of the phonological representations of spoken words as well as the learning of new words. Rehearsal takes place through the act of subvocal repetition and helps to maintain material in the phonological store. Additionally, subvocalization can be used to place and retain visually presented material such as words or nameable pictures in the phonological store. The phonological loop is widely viewed as aiding speech comprehension, especially in taxing conditions, and long-term phonological learning such as vocabulary development (Baddeley, 1992).

The second slave system of working memory, the visuospatial sketchpad, provides temporary storage and manipulation of visual, spatial, and perhaps kinesthetic information so a combined representation can be formed. While the connection may not seem as straightforward as the one between the phonological loop and language, the visuospatial sketchpad has also been suggested to play a role, for some types of material, in language comprehension (Baddeley, 2003). In a quite basic way the sketchpad may assist with the acquisition of common conventions of reading such as maintaining the representation of a page and facilitating tracking as the reader's eyes move across and down a page.

The two slave systems, then, are responsible for the storage and manipulation of verbal-acoustic and visual-spatial information. A third component, the central executive, serves in a supervisory manner to coordinate these systems. As a limited capacity system in the working memory model, the central executive coordinates a wide range of activities including processing and storing information and managing concurrent cognitive activities by means of controlling attention, inhibiting undesired responses, and shifting between tasks (Baddeley, 2003).

While this three-component model of working memory proposed by Baddeley and Hitch in 1974 provided a basic outline for understanding memory for a number of years, over time it became evident that this model did not completely account for the way in which information was integrated. By the 1990s, in an effort to explain the ability to combine visual and verbal codes and to link them to representations in long-term memory as well as the ability to store quantities of material that seemed to exceed the parameters of the visuospatial and phonological subsystems, the model was redefined to include a fourth component known as the episodic buffer (Baddeley, 2000). As a limited-capacity system controlled by the central executive, the episodic buffer accesses long-term memory information, thus providing a temporary storage system that allows for combining and integrating information from the subsystems, and thereby different modalities, into single multi-faceted chunks or “episodes.” The episodic buffer is thought to represent conscious awareness while the central executive maintains attentional control (Baddeley, 2003).

The connection between working memory and other cognitive functions has been well documented, and findings from numerous studies have indicated that measures of working memory reliably predict performance in a variety of cognitive and ability tasks such as reading comprehension, language comprehension, vocabulary learning, note-taking, writing and spelling (Adams & Gathercole, 2000; Baddeley 2003; Baddeley, Gathercole & Papagno, 1998; Montgomery, 1995; Montgomery, 2002). Fry and Hale (2000) presented a review of studies to explain the relationship between working memory, processing speed, and fluid intelligence. They reported that the age-related increase in raw scores on intelligence tests which occurs through childhood and adolescence seems in large part due to increases in processing speed but that nearly all of that influence appears to be mediated through the effect of speed on working memory. The authors thus suggested the idea of “a cognitive developmental cascade” (Fry & Hale, 2000, p.30) to help to explain the important role working memory may play in other tasks of cognitive function.

Baddeley et al. (1998) highlighted the importance of the phonological loop in language learning and provided data to illustrate a relationship between the vocabulary level of children and their short-term memory performance as measured by Digit span and nonword repetition tasks. They further described experimental word learning studies conducted with adults. Their findings indicated that word length and phonological similarity affect phonological loop performance under certain conditions; longer, unfamiliar phonological forms were more difficult for participants to remember and reproduce. A similar difficulty was encountered when subjects studying a foreign language attempted to learn unfamiliar vocabulary that was phonologically similar. In both situations, the phonological loop must provide temporary storage of unfamiliar phonological material, and the added load of length or similarity resulted in a decrease in performance (Baddeley et al, 1998).

The role that the phonological loop plays in storing information is likely important not only for vocabulary learning but also in the acquisition of syntactic knowledge. Indeed, the combination and interdependence of articulation and phonological memory would be expected to influence length of utterances and the complexity of grammatical constructions in addition to expressive vocabulary skills (Adams & Gathercole, 2000). Children are exposed to a multitude of syntactic patterns which are first held in phonological working memory then eventually stored as long-term memory representations that serve as a basis for the abstraction of syntactic rules and are used as models for their own unique utterances. The capacity of the phonological loop to store temporary representations therefore impacts the speed and accuracy of syntactic development (Spiedel, 1993).

One test that has become widely accepted in assessing phonological memory is the Children's Test of Nonword Repetition (CNRep), which is more consistently linked with language skills than other simpler verbal tasks containing phonological memory components such as auditory digit span (Gathercole, Willis, Baddeley, & Emslie, 1994). For the CNRep, subjects are presented auditorily with nonwords that are 2, 3, 4, or 5 syllables in length and required to provide an immediate repetition of the stimulus. The ability to reproduce the nonword is a complex task requiring the combination of auditory, linguistic, articulatory, and cognitive processes without the use of visual cues or prior linguistic exposure (Carter, Dillon, & Pisoni, 2002).

Additional findings have revealed a relationship between nonword repetition performance and language and/or reading abilities. In a study with children of preschool age, a significant correlation was revealed between the number of different words used, as obtained through a language sample, and the ability to repeat nonwords that were three syllables in length (Adams & Gathercole, 1995). The authors maintained, therefore, that a relationship exists between productive vocabulary and phonological memory. Based upon these findings, it appears that children with better phonological memory skills produce a wider variety of grammatical forms. Conversely, children exhibiting poorer phonological working memory abilities may require repeated presentations of a new grammatical form before they are able to correctly imitate and incorporate the word into their vocabulary. This view is consistent with that of other researchers who have proposed that the ability to temporarily store the phonological form of a novel word in working memory is vital to the long-term learning of that word and ultimately to vocabulary acquisition (Gathercole & Baddeley, 1989).

In a study of reading disabled children, Roodenrys and Stokes (2001) provided support for the idea that phonological working memory may play a part in reading development as well. A group of 16 reading disabled children were matched for chronological age with another group of 16 children and for reading level with a different group of 16 children. All subjects were asked to perform a variety of tasks including a reading task, the CNRep, and a memory span test. Results revealed significantly poorer performance by the reading disabled group on the memory span and nonword repetition tasks when compared to their age-matched peers. The differences between the reading disabled group and the reading-age matched peers, however, were not significant. The authors suggested that poorer performance on the phonological tasks of memory span and nonword repetition resulted from an underdeveloped use of long-term phonological knowledge by the younger readers as well the disabled readers (Roodenrys & Stokes, 2001). In summary, it seems apparent that the phonological loop plays an important role in the development of language and reading ability.

Similarly, the visuospatial sketchpad has been linked to language abilities in some studies. Results from a study of subjects with Williams syndrome--known to produce impaired visuospatial processing but thought to have no impact on verbal skills--suggest that the maintenance and manipulation of information in the visuospatial sketchpad can assist with language comprehension, especially for grammatical structures which include spatial terms such as prepositions (Baddeley, 2003). Additionally, Adams and Gathercole (2000) found an association between language performance and measures of visuospatial short-term memory, with subjects possessing high nonword repetition abilities performing better on tasks requiring recall of visuospatial information as compared to subjects in a low nonword recall group.

The third component of the Baddeley and Hitch model of working memory, the central executive, coordinates the operation of the phonological loop and the visuospatial sketchpad and in doing so provides a crucial link between memory ability and other cognitive functions (Baddeley, 1992). Input from both slave systems is coordinated by the central executive and integration is facilitated by the episodic buffer. Together these processes are referred to as executive control. Some aspects of executive control include the ability to control attention, to inhibit responses to inappropriate or irrelevant stimuli, to manage or shift between simultaneous tasks as necessary, and to access and manipulate information held in long-term memory. Executive function is the term used to describe the system responsible for planning, decision-making, monitoring, and anticipating and is related to the prefrontal cortex (Funahashi, 2001).

Thus the term working memory, as it has evolved over the years, is recognized as an important component of language learning. Verbal working memory is controlled by the phonological loop whereas visual-spatial working memory operates within the visuospatial sketchpad. Both are controlled by the attentional system known as the central executive which is capable of binding information from multiple sources. The episodic buffer contributes by both feeding information into and retrieving information from working memory and subsequently integrating representations from working memory and long-term memory language processing systems. In combination, these systems comprise what is generally referred to as working memory: "a brain system that provides temporary storage and manipulation of the information necessary for such complex tasks as language comprehension, learning, and reasoning" (Baddeley, 1992, p. 255).

Sequence Learning

Sequence learning refers to the ability to learn structured or statistical patterns and is a basic aspect of human cognition (Kaufman, DeYoung, Gray, Jimenez, Brown, & Mackintosh, 2010). Language is comprised of a series of sounds combined according to a set of complex rules or relations into meaningful units, yet for most children proficiency in spoken language is acquired in a natural and effortless manner. It seems plausible then that sequence learning ability has an impact on language acquisition, and findings from a number of studies lend support to this idea (Conway & Pisoni, 2008; Conway et al., 2009; Furth & Pufall, 1966; Reber, 1967).

Although a connection to language acquisition may be generally accepted, there is not a consensus as to whether sequencing ability is an innate skill or one that depends upon experience. The readily observed fact that language develops rapidly and is drawn from incomplete representations has led a number of researchers to propose sequence learning as an innate skill which thereby occurs independently from experience. In support of this view, Dominey (1997) suggested that humans are predisposed for sequence learning which provides a foundation for the general sequence processing aspect of language. Others contend that experience plays a role in sequence learning and language development as well. In support of this latter view, Saffran, Aslin, and Newport (1996) presented findings from a study in which 8-month olds were presented with concatenated speech. Through use of a familiarization-preference procedure, infants were exposed to auditory stimuli and thereby provided with a potential learning experience. Following the familiarization phase, the infants were presented with one set of stimuli that contained items from the familiarization and one set that did not. Results revealed that infants were able to extract the sequential statistical information necessary to recognize the difference between novel and familiar syllables. This finding provided evidence of experience-dependent learning in addition to experience-independent or innate mechanisms which may aid in the acquisition of language. The authors proposed that if exposure to these complex sequential patterns is essential to language learning, then indeed the number of experiences gathered by a child in the first year of life potentially plays a very significant role in development (Saffran et al., 1996).

In summary, research findings suggest that the ability to learn structured sequential patterns may represent an underlying skill which contributes to the acquisition of language. While sequence learning may be largely implicit in nature, experience likely plays a role in its development as well (Saffran et al., 1996).

Performance by Children Who are Deaf or Hard of Hearing

The previous section presented findings illustrating the connection between various cognitive functions and language performance. Functions related to language ability include overall working memory ability, phonological memory ability, executive control, and sequence learning ability. In order to uncover possible explanations for the poorer language performance often demonstrated by children who are deaf or hard of hearing it is necessary to consider performance by this group on specific tasks which enlist these abilities.

Working memory and sequence learning.

Working memory capabilities in children who are deaf or hard of hearing have been the subject of investigation over the years (Dawson et al., 2002; Harris, & Moreno, 2004; Johnson & Goswami, 2010; Parasnis, Samar, Bettger, & Sathe, 1996; Pisoni 1999; Pisoni & Geers, 2000; Sterritt, Camp, & Lipman, 1966; Watson et al. 2007; Wayne, Long, & Dowaliby, 1997; Willstedt-Svensson et al. 2004). Whether the focus has been on visuospatial or verbal working memory, the goal has been to discover elements which may help to explain the differences in performance of children who are deaf or hard of hearing as compared to their typically hearing peers.

Studies implementing auditory working memory tasks have revealed, not surprisingly, that subjects who are deaf or hard of hearing frequently perform at a level below typically hearing peers (Pisoni, 1999; Pisoni & Geers, 2000), yet upon closer examination, all of the differences are not attributed to auditory abilities alone. Pisoni and Geers (2000) conducted a study with 43 cochlear implant users eight to nine years of age. Correlational analysis of auditory digit spans revealed moderate to strong positive correlations between the digit span subtests of the Wechsler Intelligence Scale for Children (WISC) and four measures of spoken language processing: speech perception, speech intelligibility, language tests, and reading performance. The conclusion was that short-term working memory may contribute, over and above any differences in basic discrimination skills, to the way speech is processed, that is "perceived, encoded, rehearsed, stored, transformed and manipulated" (Pisoni & Geers, 2000, p. 337), and therefore may account for some of the differences in language outcomes across implant users. In addition, subjects in this study who were educated in a listening and spoken language environment where instruction does not include the use of sign language demonstrated longer digit spans than those taught with the Total Communication method which utilizes sign language in conjunction with spoken language. This difference suggests that working memory abilities are dynamic and may be shaped or changed by environment and language-related experiences.

Other auditory tasks with similar findings have added support to the idea that differences in working memory may impact other cognitive processes such as reading, learning and allocating attentional resources (Watson et al., 2007). Watson et al. (2007) reported poorer performance on three measures of working memory by 15 children who had received cochlear implants compared to 19 children with typical hearing. The tasks consisted of a nonword repetition task and both forward and backward digit spans. In addition to group-related differences, analyses also revealed highly significant correlations between the nonword task and both digit span tasks for the group with typical hearing. For children in the cochlear implant group, however, no such correlation between nonword repetition and the digit span tasks was discovered even after age of implant and duration of use were included as covariates. To account for this finding, the authors proposed a difference in processing strategies among the implant group which may include a breakdown in the way that aspects of working memory assist with verbal memory tasks.

Complex working memory ability in children with cochlear implants was assessed in a study by Willstedt-Svensson et al. (2004) through a sentence completion and word recall task. The task required subjects ages five to 11 years to listen to seven sentences as they were read out loud by an examiner and to complete each sentence with an acceptable word. Following a set of three and then four sentences, the subjects were asked to recall the completions. Results of this test correlated significantly with novel word learning and both receptive and expressive grammar. The limitations in working memory revealed in this study suggest speech and language training for children who are deaf or hard of hearing should be informed by cognitive theory (Willstedt-Svensson et al., 2004).

Other auditory tasks which merely require short-term memory have been revealed differences as well. Ling (1975) reported significant differences between a group of children with typical hearing and a group who were deaf or hard of hearing on the recall of auditory sequences. Despite demonstrating the ability to hear and repeat individual syllables, subjects who were deaf or hard of hearing recalled sequences of spoken syllables more poorly than subjects with typical hearing. This finding suggested that poorer performance by the subjects who were deaf or hard of hearing was due in part to an inadequate process of coding information for storage and retrieval from short-term memory. In other words the deaf or hard of hearing subjects did not seem to be utilizing a rehearsal strategy to aid in their memory of verbal sequential stimuli.

Studies such as those described above consistently reveal differences between subjects with typical hearing and those who are deaf or hard of hearing on auditory memory and sequencing tasks, yet results from studies of visual memory abilities have been mixed (Dawson et al., 2002; Johnson & Goswami, 2010; Logan, Maybery, & Fletcher, 1996; Parasnis et al., 1996; Sterritt et al., 1966). Of key significance in visual memory studies is the type of task employed; difficulties for subjects who are deaf or hard of hearing often arise with stimuli that promote verbal coding of information, which can include nameable objects but also numbers or colors (Dawson et al., 2002) as well as with tasks requiring serial order memory (Furth & Pufall, 1966). Studies revealing deficits among children who are deaf or hard of hearing in the ability to process and discriminate sequences, a characteristic skill of language learning (Conway et al, 2011; Furth & Pufall, 1966; O'Connor & Hermelin, 1973) may provide insight into additional cognitive factors contributing to the variance in language performance.

On a test of visual memory requiring subjects to draw one or more geometric figures from memory, Parasnis et al. (1996) found no main effect or interaction between children who were deaf or hard of hearing and those with typical hearing. In contrast, when these same subjects were shown cards displaying a sequence of digits—stimuli which lend themselves to verbal coding—and then required to reproduce the sequence on a piece of paper, the results revealed a significantly shorter memory span by the deaf or hard of hearing subjects. The finding that the difference between the two groups did not extend to the task requiring only visual memory discounts any claim of a general short-term memory deficit for the deaf or hard of hearing group. Similar results emerged in a study of 25 adults who were deaf or hard of hearing and 20 who had typical hearing, all of whom were fluent users of Australian Sign Language. The group with typical hearing performed significantly better on both free and serial recall tasks with verbal stimuli presented as written words or signs. No group differences were revealed, however, on a computerized version of the Corsi visual-spatial memory task (Logan et al., 1996). Additional analyses revealed that reading level, as measured by the passage comprehension section of the Woodcock Reading Mastery Test, was significantly correlated with serial recall of both the sign and word tasks as well as free recall of the visuospatial task. Here again, the nature of visual stimuli seemed to affect performance by subjects who were deaf or hard of hearing, with verbal stimuli being remembered less readily. Results from these studies point to a possible failure to employ a verbal rehearsal strategy to aid the memory process.

Dawson et al. (2002) assessed short-term memory abilities along with receptive language abilities of cochlear implant users and found that children using cochlear implants performed more poorly than typically hearing peers on a picture sequence memory task but not on a visual memory task requiring the imitation of hand movements. Consistent with findings in other studies, the children with normal hearing performed better than the implant users on visual short-term sequential memory tasks that lent themselves to verbal coding. The subjects were presented with pictures of a fish and a dog in a sequence and required to replicate the sequence with a series of button presses. Despite the fact that subjects were not required to provide a spoken response, performance by the cochlear implant group was significantly poorer than the group with typical hearing. Since the stimulus items could readily be coded as verbal representations in memory, it is likely that the group with typical hearing employed a speech-based rehearsal strategy. Performance for the two groups was similar on visual short-term memory tasks that required imitation of hand movements which were less likely to be verbally coded. The authors also computed difference scores by subtracting visual from auditory memory performance and found no significant difference between the two groups, indicating that the deficit for the implant group was not specific to the auditory modality. Furthermore, visual spatial memory as measured by a subtest of a nonverbal

IQ test, provided the strongest prediction of receptive language scores (Dawson et al., 2002).

The previous studies of visually presented stimuli have indicated a deficit by children who are deaf or hard of hearing for remembering information that can be verbally coded, yet there is evidence that this difficulty extends to sequentially presented stimuli regardless of the verbal or nonverbal nature of the stimuli or the mode of presentation. Steritt et al. (1966) investigated recall of auditory and visual stimuli with a group of children who were deaf or hard of hearing and a group of typically hearing children ranging in age from three years nine months to seven years three months. Results revealed that children with typical hearing performed better than children who were deaf or hard of hearing on both auditory and visual pattern reproduction tasks. The finding that differences are not modality specific supports the authors' hypothesis that a period of auditory deprivation can lead to deficits in temporal patterning ability.

Furth and Pufall (1966) employed a number of sequence activities which produced similar findings. Three one inch by two inch cards containing black nonsense figures were presented in two different sequence conditions. Subjects ages six and seven were instructed to reproduce the sequence. In the successive presentation condition, the three cards were displayed individually for one second with a one second interval between presentations. For simultaneous presentations, the entire sequence of three cards was presented at once for a period of three seconds. Results revealed significantly poorer sequence replication on the successive sequence task by children who were deaf compared to a group of typically hearing children the same age. However, recall by the two groups was not significantly different for the sequences that were presented simultaneously. Typical hearing generally leads to normal development of language skills. It is possible that linguistic practice provides experience with sequentially presented material thus accounting for the better performance by the hearing group on the successive sequencing task. The poorer performance by subjects who were deaf or hard of hearing on sequential sequencing tasks, therefore, may be attributed to "early deafness or linguistic deficiency," (Furth & Pufall, 1966, p. 441).

Sequential learning has likewise been addressed in more recent studies of children who are deaf or hard of hearing (Conway, Karpicke, Anaya, Henning, Kronenberger, & Pisoni, in press; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). A group of children with typical hearing outperformed an age-matched group of cochlear implant users on a set of fingertip tapping tasks designed to measure basic sensorimotor sequencing skill (Conway, et al., in press) as well as on a visual implicit learning task (Conway et al., 2011). The study of implicit sequence learning ability included 25 subjects who were deaf or hard of hearing and had received cochlear implants and 27 subjects with typical hearing (Conway et al., 2011). A touch screen monitor was used to display four squares of different colors. The squares flashed one at a time to present a sequence which the subjects were instructed to replicate. Unbeknownst to the subjects, the sequences presented were generated by an artificial grammar. A learning and a testing phase were imbedded into the task, with scores on the testing phase allowing for the calculation of an implicit learning score. The difference between the number of correct replications for sequences which followed the grammatical rules and for those which were ungrammatical in nature provided an implicit learning score. Results revealed that fewer than half of the implanted children compared to 75% of the children with typical hearing displayed learning on the task. Additionally, a significant correlation emerged between implicit sequence learning and several measures of spoken language processing. Along with the results from Furth and Pufall (1966), these findings provide support for the idea that language ability and sequencing ability are closely related.

O'Connor and Hermelin (1973) examined sequence abilities in deaf or hard of hearing subjects as well. A display box was used to present a series of three numerals one at a time in one of three locations—left, middle, or right. Following each sequence presentation, participants were required to write down the sequence they had seen. Participants who were deaf or hard of hearing were able to recall the numerals presented with the same accuracy as the subjects with typical hearing, but a difference in the manner of response emerged. Children with typical hearing recorded their responses primarily in temporal order reflective of the order in which the numbers had been presented. The children who were deaf or hard of hearing, however, almost exclusively replicated the spatial order or location of the numbers without regard to the order of appearance. Because all stimuli were presented visually, no difference in response style based upon hearing status had been anticipated. One possible explanation provided by the authors for the spatial rather than temporal response by the subjects who were deaf or hard of hearing was the absence of an adequate language system to allow the information to be analyzed and stored in a linguistic form (O'Connor & Hermelin, 1973).

More recently, Johnson and Goswami (2010) reported age appropriate visual memory skills for subjects who were deaf or hard of hearing as measured by standard scores on the Leiter-R Memory Screen task. The study included 19 children with typical hearing as well as 43 subjects who were deaf and had received cochlear implants at an early (2.5 years) or late (5 years) age, or wore hearing aids. The memory screen task consisted of a picture association task and a spatial sequencing task. Although all subjects who were deaf received standard scores in the average range, performance by the early cochlear implant group was the best. Furthermore, significant correlations were revealed between the Leiter-R visual memory tasks and reading comprehension, orthographic knowledge, and digit span. The authors also found visual memory skills to be one of the factors, in addition to phonological and language skills, associated with reading development in children with typical hearing. The finding that earlier implanted subjects performed better suggests that the length of time that a child experiences auditory deprivation may affect the degree to which cognitive functions such as sequence and memory abilities are impacted.

Evidence that working memory (Pisoni & Geers, 2000) and sequence learning abilities (Conway & Pisoni 2008; Furth & Pufall, 1966; O'Connor & Hermelin, 1973) may underlie language skills is of particular importance because it implies that despite advances in technology, audibility and discrimination alone cannot predict successful language outcomes for children who are deaf or hard of hearing. Sound is a temporal and sequential signal (Hirsh, 1967) and children with typical hearing receive nearly continuous exposure to serial order stimuli. For children who are deaf or hard of hearing these stimuli may be absent or significantly diminished in quality. Furth and Pufall (1966) proposed that the ability to process and discriminate sequences was a key component of language learning, and Conway and Pisoni (2008) presented empirical evidence supporting the claim that implicit learning of complex sequential patterns is an underlying factor in spoken language processing. A period of auditory deprivation experienced by children who are deaf or hard of hearing, therefore, may result in a failure to receive the temporal pattern experience necessary for typical development of speech and language (Conway et al, 2009; Sterritt et al., 1966).

Phonological memory abilities.

The phonological loop, as previously described, is a key component in the Baddeley and Hitch model of working memory. It is particularly suited for retention of sequential information and is responsible for subvocal rehearsal and maintenance of language based information. In an effort to understand differences in performance on memory and language tasks, a number of studies have sought to determine the role of the phonological loop for subjects who are deaf or hard of hearing by specifically examining the use of rehearsal strategies (Bebko, 1984; Conrad, 1973; Wallace & Corballis, 1973). In a study of 43 deaf students and 46 adult women with normal hearing, subjects were required to recall two sets of consonant sequences presented visually at a rate of one letter per second (Conrad, 1973). In the first set, letters were highly phonologically similar and included the following letters: B, C, D, P, T, V. The second set with low phonological similarity was comprised of the letters K, N, V, W, X, Y. Subjects with typical hearing made fewer errors on sequences that were phonologically similar, while the subjects who were deaf or hard of hearing made an equal number of errors on phonologically similar or dissimilar sequences. These findings indicate a lack of speech coding, or verbal rehearsal via the phonological loop, for the latter group and mark a clear difference in the coding strategies utilized by the two groups (Conrad, 1973).

Bebko (1984) reported similar findings in a study of all deaf or hard of hearing students. Twenty-nine students who were educated in an auditory/oral setting and 34 students educated in a total communication environment were presented with sequences of colored cards. Based upon observations of the use of cumulative rehearsal strategies, subjects were classified as Producers or Nonproducers. Producers either used overt rehearsal, manual signs alone or in conjunction with some type of verbalization, or some other memory strategy such as counting on their fingers. Spontaneous verbal rehearsal differed depending upon the educational background of the child; those educated in an oral environment began utilizing the strategy at the age of 10 to 11 while for those using total communication this skill did not emerge until age 12 to 13 (Bebko, 1984). Ages for both of these groups were in sharp contrast to data from a previous study revealing that children with typical hearing use verbal rehearsal strategies as early as age seven or eight (Bebko, 1979). Thus it is clear that even when subjects who are deaf or hard of hearing are utilizing a rehearsal strategy they are beginning to do so at a much later age than peers with typical hearing. Bebko noted the educational importance of this finding and suggested the necessity of providing students who are deaf or hard of hearing with direct instruction in the process of learning how to remember information.

In a later study including children who were deaf or hard of hearing as well as children with typical hearing (Bebko & McKinnon, 1990), a similar lag in spontaneous rehearsal was found among the former group, leading to the assertion that a certain level of language mastery is a necessary prerequisite for the employment of verbal rehearsal. Furthermore, the authors suggested that an incomplete mastery of language may be a contributing factor in the ineffective use of other cognitive strategies, a theory which may help explain, in part, the relationship between phonological memory and other skills such as reading ability. It appears then that delayed or reduced use of subvocal rehearsal strategies by children who are deaf or hard of hearing indicates differences in the phonological loop component of working memory compared to typically hearing peers. Given the relationship between phonological loop abilities and language outcomes (Adams & Gathercole, 1995; Spiedel, 1993), it is plausible that poor phonological memory ability may be one of the underlying factors responsible for poor language and reading skills often exhibited by children who are deaf or hard of hearing.

The Children's Test of Nonword Repetition (CNRep) has been identified as a useful tool in studies of working memory, vocabulary size, and reading ability with typically hearing children (Adams & Gathercole, 1995). The CNRep has also been shown to be useful as a measure of phonological ability in studies of children with cochlear implants (Carter et al., 2002; Dillon, Cleary, Pisoni, & Carter, 2004). Dillon et al. (2004) presented twenty nonword stimuli that were 2, 3, 4, and 5 syllables in length to twenty-four children with cochlear implants. Imitations were analyzed for segmental and suprasegmental characteristics. An imitation was scored as segmentally correct if all aspects of a target word were correctly reproduced. Suprasegmental features that were scored included syllable and stress accuracy. Responses were scored as syllabically correct if the number of syllables produced by a subject matched the number presented for each target word. Similarly, the stress pattern of a response needed to match that of the target word in order for the primary stress to be counted as correct. Not surprisingly, the deaf or hard of hearing subjects performed quite poorly on the segmental scoring, producing only 5% of the target words without any errors. Suprasegmental analyses, however, revealed some interesting findings. First, the accuracy to reproduce the correct number of syllables and to replicate the stress pattern of the target words was significantly correlated with performance on two open-set word recognition tests, the Banford-Kowal-Bench Sentence List Test (BKB) and the Multisylabic Lexical Neighborhood Test (MLNT) indicating the possibility that responding to the CNRep employs the same underlying linguistic processes as recognizing and repeating real words. Additionally, better performance on the nonword task was also positively and significantly correlated with higher receptive vocabulary, morphology and syntax scores on a language comprehension task, the Test of Auditory Comprehension of Language Revised (TACL-R). Finally, there was a significant correlation between forward digit span scores obtained from the Wechsler Intelligence Scale for Children (WISC) and the accurate production of syllables and stress patterns, with longer digit spans being associated with better suprasegmental imitation. These findings point to a connection between nonword repetition skills and the ability to encode, rehearse, and store items in short-term memory and the usefulness of the nonword task as a measurement in the attempt to assess and understand the linguistic abilities of subjects who have cochlear implants (Carter et al., 2002).

Watson et al. (2007) also compared performance of nonword repetition between typically hearing subjects and subjects who had received a cochlear implant. Their findings revealed positive and significant correlations between nonword repetition and both forward and backward digit spans for the typically hearing subjects. No such correlations were found for the deaf or hard of hearing group, however. For the authors this pointed to a breakdown in the way in which subcomponents of working memory contribute to a phonological memory task such as nonword repetition. The proposal that a different processing strategy results from a period of auditory deprivation for children who are deaf or hard of hearing (Watson et al., 2007) aligns with Conway et al. (2009) who proposed that sound provides a supporting framework upon which general cognitive abilities related to the representation of sequential information are built. This hypothesis, referred to as “auditory scaffolding” (Conway et al., 2009, p.275), suggests that sound plays a role in cognition that extends beyond auditory perception.

The studies outlined above reveal the difficulties of children who are deaf or hard of hearing to perform tasks of working memory, to utilize the phonological loop, to recall serially ordered items, and to remember visual information that can be verbally coded. Further study of these difficulties may ultimately aid in determining how and why these abilities differ from those of typically hearing children and may provide insight into the nature of the delays exhibited by children who are deaf or hard of hearing in developing communication skills.

Training Studies

Evidence supports the contribution of working memory (Adams & Gathercole, 1995; Spiedel, 1993) and sequence learning (Conway et al., 2009; Kaufman et al., 2010; Saffran et al., 1996) to the development of language skills. This data combined with individual differences in performance makes it important to ask the question: Can working memory and sequencing capabilities be improved and thereby positively impact language and cognitive skills? A number of studies have indeed begun to investigate this question and have implemented training tasks in an effort to determine whether working memory can be improved (Curtis & D’Esposito, 2003; Holmes, Gathercole, & Dunning, 2009; Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002; Olesen, Westerberg, & Klingberg, 2004; Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009;

Shalev, Tsal, & Mevorach, 2007; Westerberg, Jacobaeus, Hirvikoski, Clevberger, Ostensson, Bartfai, & Klingberg, 2007).

Memory training studies explore aspects of working memory capacity from both behavioral and neural functioning perspectives and implement a variety of tasks involving the temporary storage and sometimes the manipulation of visual-spatial or verbal information or both. Although the training tasks and populations have differed somewhat, the goal of these focused training programs has remained similar: to discover whether memory training tasks can improve performance beyond training to nontrained tasks of spatial and verbal working memory, attention, and other cognitive functions. Training in these studies is generally referred to as working memory training regardless of the specific components of working memory that are trained (Gathercole & Dunning 2009; Klingberg et al., 2002; Klingberg et al., 2005; Thorell et al., 2009; Westerberg et al., 2007). Furthermore, strictly speaking, some of the previous "working memory" training studies may not actually tap working memory per se because they only involve short-term storage and recall of information and not the involvement of the central executive. Following the terminology established in the extant literature, the term working memory training will be used to refer to training tasks even when they may only require spatial short-term memory and/or verbal short-term memory without apparent involvement of the central executive.

Behavioral studies.

Behavioral studies of working memory training have revealed performance changes on untrained tasks thus providing support to the notion that training on a specific task may affect broader areas of executive functioning (Gathercole & Dunning 2009;

Klingberg et al. 2005; Thorell et al., 2009; Westerberg et al., 2007; Shalev et al., 2007). Klingberg et al. (2002) set out to investigate the possibility of improving working memory capacity in children with ADHD, with the prediction that such an improvement would result in a decrease in symptoms of ADHD. In a double-blind design, fourteen subjects ages seven to 15 were divided into treatment and control groups. Training sessions were implemented four to six days per week over a period of five weeks. Sessions for the treatment group lasted about 25 minutes. Three tasks of working memory were included: a visuospatial task which required replication of a sequence of circles presented on a four by four grid, a backwards digit span task which presented digits both visually and auditorily, and a letter span task also presented auditorily. Both visual and verbal feedback was provided to the subjects. An adaptive and control group performed similar activities, but the control group completed only 10 trials per task each day in contrast to the 30 trials completed by the treatment group. Additionally, the difficulty level was adapted or adjusted as a result of performance throughout the course of the training for the adaptive group only. Results showed that adaptive training led to improvement on a nontrained task of visuospatial working memory as well as on a Stroop or inhibition task and the Raven's Progressive Matrices. A reduction in the number of head movements during a continuous performance task was also reported for the adaptive group. A smaller, second experiment in this study included university students who had not been diagnosed with ADHD. Results of this study revealed a similar trend for improvement on the nontrained test of working memory, the Stroop task, and the Raven's task. Such findings reinforce the notion that working memory is a dynamic trait subject to improvement through training and that training can generalize to nontrained tasks (Klingberg et al., 2002).

Based in part upon previous studies in which training improved working memory performance on nontrained tasks as well as findings that indicated an increase in cortical activity following working memory training (Olesen et al., 2004), Klingberg et al. (2005) implemented a visuospatial working memory task and a verbal task with children diagnosed with ADHD. The visuospatial task involved remembering the position of objects on a four by four grid, and the verbal task required remembering phonemes, letters, or digits presented both visually and auditorily. Responses were made on a computer screen through the use of mouse clicks. Tasks were adapted in length to match the working memory span of the subjects on a trial-by-trial basis for the treatment group but remained at two or three items for the control group. At post training sessions both five to six weeks and then three months following the baseline measures, subjects in the treatment group showed significant improvement compared to the control group on the visuospatial Span board task. Additionally, the treatment group showed improvement on a number of executive tasks including digit span, Stroop time, and Raven's matrices. These results are in line with those of other studies (Olesen et al. 2004) which revealed a transfer from training tasks which did not include problem-solving or response inhibition to nontrained executive tasks. Klingberg (2010) proposed that common recruitment of the prefrontal and parietal cortices in tasks of working memory and reasoning may explain the generalization from visuospatial training to reasoning and response inhibition.

Additional support of this transfer comes from a study of 18 adult stroke patients (Westerberg et al., 2007). During daily training sessions, subjects completed a number of computerized working memory training tasks comprised of both visual and auditory stimuli. Some of the tasks were visuospatial in nature while some included a verbal element such as nameable objects or numbers. A neuropsychological test battery was administered before and after implementation of the training program. At the end of five weeks of 40 minute daily training sessions, subjects showed significant improvement from pre to post training on performance of nontrained tests of working memory, specifically the Span board and Digit span tests, compared to a similar age control group.

More recent studies (Holmes et al., 2009; Thorell et al., 2009), have presented similar findings in children with low working memory and with preschool age children. Holmes et al. (2009) selected children ages eight to 11 with scores at or below the 15^{th} percentile on tests of listening recall and backward digit recall, both measures of verbal working memory. Two groups completed computerized tasks requiring the temporary storage of visuospatial information, verbal information, or combined visuospatial and verbal information. As with the Westerberg et al. (2007) study, training included both visual and auditory presentations. Subjects in both groups completed 35 minutes of training for 20 days over a five to seven week period. In one group the training was adaptive in nature allowing the difficulty of the task to match the subject's current memory span on a trial-by-trial basis. The other group was presented with a non-adaptive version of the tasks that was set at a fixed sequence length of two items per trial throughout the entire training period. Results revealed a significant improvement by the adaptive training group on tasks of verbal short-term memory, verbal working memory, and visuospatial working memory as compared to members of the non-adaptive group.

Furthermore, the gains which resulted from training remained significant for the adaptive group six months after training (Holmes et al., 2009).

In another adaptive training task, Thorell et al. (2009) trained four and five year olds with a visuospatial memory task. Subjects were presented with a visual sequence on a computer screen and then asked to replicate the order and location of the lighted sequence through the use of mouse clicks. Training took place for fifteen minutes each day of preschool attendance for a five week period. Improvement occurred from pre to posttest measures on the Span board task, a nontrained test of visuospatial working memory. Improvement also occurred for a word span task identical in nature to the digit span subtest of the WISC-III but which required repetition of unrelated nouns instead of digits. The results from this study revealed two important findings. First, children of preschool age showed improvements in cognitive functions following working memory training, though the authors admitted that additional studies should be designed to investigate any lasting effects. Second, despite the fact that training only involved tasks of visuospatial memory, a transfer effect to tasks of verbal working memory occurred.

Bauernschmidt, Conway, and Pisoni (2009) utilized the color sequence touch screen monitor task previously described with a group of 31 subjects ages 18 to 33 in a sequence learning training study which also revealed effects of adaptive training. Subjects were randomly divided into three groups which determined the type of color sequences to be presented. The adaptive, constrained group was presented with sequences determined by an artificial grammar. Sequence length increased or decreased according to a two-up, two-down metric. In the pseudo-random adaptive condition, sequences also changed length based upon the correctness of a response, but they were not governed by an artificial grammar. Sequences in the pseudo-random, non-adaptive condition were not generated by an artificial grammar and varied in length randomly between four and 16 elements. Unlike previous studies described above, the training phase in this study was extremely short, taking place over a period of just four days. Analyses of a spoken sentence perception task, the Stroop test, the Raven's matrices, and an implicit learning task suggested that subjects benefitted from the adaptive condition and even more so from the probabilistic nature of the constrained sequences in the adaptive condition. The positive effects of the combined probabilistic structure and adaptive format provide implications for future working memory training studies (Bauernschmidt et al., 2009).

Finally in a study of cochlear implant subjects, Kronenberger et al. (2010) reported positive effects from a computerized training program. This trial study was designed to investigate the feasibility and efficacy of the Cogmed Working Memory Training program for use with children who had received cochlear implants. Nine subjects ranging in age from seven to 15 years took part in screening and pretraining assessment sessions followed by training and then two post training assessment sessions. The training included 12 computer-based activities requiring auditory, visuospatial or combined auditory-visuospatial short-term and working memory skills. Each training session presented eight of the 12 possible exercises and took place in homes of the participants for 30 to 40 minutes per day five days each week for a period of five weeks. Similar to other training programs, the Cogmed exercises increased in level of difficulty as subjects progressed. The authors reported a significant improvement on measures of digit span and spatial span following training. Additionally the participants showed a transfer from training to working memory tasks by improving on the language task of sentence repetition. This improvement remained significant at a six month follow-up assessment. It was noted that the study lacked a placebo group and that other assessments of speech and language ability may be desirable. The authors asserted, however, that these results lend further support to the idea that a period of auditory deprivation and the resulting atypical auditory experiences for cochlear implant users—and arguably all children who are deaf or hard of hearing—may indeed have a broad-reaching impact on the development of a host of neurocognitive functions such as attention, sequential processing, working memory, and other tasks of executive function (Kronenberger et al., 2010). Positive effects of training, therefore, give promise to the idea of improving these cognitive functions and subsequently the skills which enlist them.

Additional training studies have focused on skills other than working memory with positive effects as well. Temporal processing was the target of one such study (Merzenich, Jenkins, Johnston, Schreiner, Miller, & Tallal, 1996). Based upon findings which revealed deficits in temporal processing by children with language-learning impairments and guided by the hypotheses that this deficit resulted from atypical perceptual learning, Merzenich et al. (1996) designed a training regimen which included high interest audiovisual activities. One task required replication of a nonverbal sound sequence through touch screen button presses. The other was a forced-choice task requiring the subject to identify the sequence position of a target combination in a contrasting consonant-vowel combination. Training on both tasks was adaptive in nature. Following intensive practice totaling five to 10 hours over a 20 day period, subjects showed significant improvement on a test of temporal processing ability. Because deficits in temporal processing contribute to abnormal language learning (Merzenich et al., 1996) these findings point to the potential for improving language function through adaptive sequence training.

A study by Shalev et al. (2007) was aimed at improving attentional functions of children diagnosed with ADHD. The study was motivated by the fact that children with ADHD often receive low grades in academic subjects and low grades on standardized tests of reading, spelling, written language and math as well as the belief that this deficit results in part from a poorly functioning attentional system. Thirty-six children ages six to 13 were divided into three groups. Twenty took part in a computerized progressive attentional training (CPAT) program consisting of 16 one-hour sessions over an eight week period, while 16 formed a control group that played computer games and performed a variety of pen and pencil activities (Shalev et al., 2007). Tasks were both visual and auditory in nature. Measures on pre and post treatment evaluations revealed a significant improvement on nontrained measures of reading comprehension and passage copying for the children in the treatment group. The authors note two key components of the treatment: subjects were provided feedback throughout the sessions and the exercises were adaptive in nature. The authors credited use of the attentional training program with improvements on the copying and reading comprehension tasks. Improvements on these tasks which require the efficient use of attentional systems were not displayed by the control group. Additionally, ratings obtained through parental reports revealed a substantial reduction in symptoms of inattention and hyperactivity for children in the treatment group following treatment (Shalev et al., 2007).

In summary, the adaptive training studies presented above provide evidence of improvement on a variety of nontrained visual and verbal tasks of working memory as well as prefrontal and executive function tasks of complex reasoning and inhibition. While many studies have incorporated both visual and auditory components into their training (Klingberg et al., 2002; Klingberg et al., 2005; Kronenberger et al., 2010; Westerberg et al., 2007), improvement has also been shown following training that was purely visual in nature (Thorell et al, 2009). In addition, training studies which did not focus on working memory skills revealed improvement for tasks of temporal sequencing (Merzenich et al., 1996) and attention (Shalev et al., 2007). Working memory is a key component of language development and language is sequential in nature, therefore improvement from training on phonological memory and sequencing tasks has the potential to carry over to more general language-related skills including vocabulary and syntactic development.

Neuroimaging studies.

The previous section demonstrated the behavioral effects of training programs on a variety of memory and sequencing tasks. Other studies have investigated the neural mechanisms underlying these visible effects (Curtis & D'Esposito, 2003; Funahashi, 2001; Olesen et al., 2004; Smith & Jonides, 1999). It is widely accepted that levels of brain metabolism increase and rapidly achieve adult levels as children mature, yet not all areas of the brain develop at the same rate (Gathercole, 1999). The frontal lobe, and more specifically the prefrontal cortex, is cited as a late maturing cortex that does not reach full maturity until adolescence (Fuster, 2001). The prefrontal cortex is thought be responsible for mediating working memory processes and implementing executive processes and as such plays a large role in higher cognitive functions (Smith & Jonides, 1999). To review, executive function describes the system responsible for planning, decision-making, monitoring, and anticipating and is related to the prefrontal cortex (Funahashi, 2001). Executive control is necessary for the coordination of the motor, perceptual, and memory processes in order to achieve successful functioning and is a key function of the central executive in the Baddeley and Hitch model of working memory. Key among the executive processes are the control of cognition and attention which involve switching from one source of information to another or focusing on one source, temporally organizing responses to immediate stimuli, monitoring current information, accessing and manipulating information in long-term memory, and planning complex tasks in order to achieve a future goal (Funahashi, 2001).

A number of neuroimaging studies support the connection between working memory capacity and the prefrontal cortex. Some have provided evidence to suggest that even training tasks that appear to involve only short-term storage of information actually result in changes to the neural functioning of the prefrontal cortex, an area believed to mediate the processing of the central executive (Curtis & D'Esposito, 2003; Olesen, et al., 2004). Olesen et al. (2004) had subjects practice three computerized visuospatial memory tasks for a period of five weeks. Use of functional magnetic resonance imaging (fMRI) before, during, and after training showed increased activity in the prefrontal and parietal cortices as a result of training. Similarly, Curtis and D'Esposito (2003) reported sustained prefrontal cortex activity during delay periods preceding the response portion of a visual working memory task. The former study included neuropsychological tests as part of the pre and post training evaluation. Subjects showed significant improvement in performance on the Span board task and the Digit span task, and in time on the Stroop test, illustrating not only improvement on a similar type task but also transfer to nontrained tasks of working memory as well. Authors from both studies asserted that cortical prefrontal activity is a component of working memory and increases in activity during or following working memory training suggesting plasticity in the neural systems supporting working memory (Olesen et al., 2004).

Given the evidence of prefrontal activity and its relation to executive function, Funahashi (2001) proposed that the prefrontal cortex could be the center for executive control and as such was responsible not only for storing and processing information, but also for assessing the input and providing information to neuronal systems to direct the processing of information in these systems. The processes of perception, motor control, and memory must be coordinated to accomplish the tasks of anticipating, planning, monitoring, and decision-making (Funahashi, 2001). The evidence suggests that improvement on a visuospatial training task affects neural functioning of the prefrontal cortex and thus, perhaps by extension, executive functions more generally. The involvement of the prefrontal cortex in executive processes (Funahashi, 2001; Smith & Jonides, 1999) and evidence of increased prefrontal activity during spatial memory tasks (Curtis & D'Esposito, 2003; Funahashi, 2001; Olesen et al., 2004; Smith & Jonides, 1999) thus lend support to the notion that improved performance on memory and executive function tasks following training on a visuospatial task may carry over to other tasks involving different skills, including those requiring verbal memory or executive processing.

Neuroimaging studies provide additional support to the behavioral studies with physical evidence of changes in the brain during or following training. These data support the claim that cortical plasticity is potentially an underlying contributor to improvement on cognitive and memory tasks and that improvement in prefrontal cortex functioning and the subsequent affect on different cognitive tasks may indicate a multimodal aspect of the prefrontal cortex (Olesen et al., 2004). Results from other studies have demonstrated that verbal, object, and visual working memory stimulus materials activate identical prefrontal areas (Owen, Sterns, Look, Tracey, Rosen, & Petrides, 1998; Postle, Berger, Taich, & D'Esposito, 2000). Previously outlined findings revealed that working memory (Adams & Gathercole, 1995; Spiedel, 1995) and sequencing ability (Conway et al., 2009; Saffran et al., 1996) are both related to language performance. Additionally, there is evidence that training leads not only to improvement on a trained task but also results in transfer to other tasks of working memory or executive function. If working memory and sequence learning abilities are not necessarily fixed as these results indicate, then the utilization of training tasks with children who are deaf or hard of hearing offers promising implications for the improvement of language skills.

This introductory section has focused on a number of key issues related to the varied and often poor language outcomes of children who are deaf or hard of hearing. It has been noted that normal hearing acuity affords exposure to serially ordered events and as such can be considered the foundation upon which sequential learning is built (Conway et al., 2009; Furth & Pufall, 1966). A period of auditory deprivation can result in cortical reorganization and subsequent deficiencies in sequencing ability which in turn can lead to atypical development of speech and language skills (Sharma & Dorman, 2006). A number of studies have revealed delayed or deficient performance on a variety of memory, sequencing, and executive control tasks by children who are deaf or hard of hearing. Neuroimaging and behavioral studies have demonstrated success in the use of interventions aimed at improving working memory skills. The involvement of the prefrontal cortex in executive processes (Funahashi, 2001) and evidence of increased prefrontal activity during spatial memory tasks (Curtis & D'Esposito, 2003; Funahashi, 2001; Olesen et al. 2004; Smith & Jonides, 1999) support the notion that training on a visuospatial task may carry over to other tasks involving different skills, including those requiring verbal memory or executive processing. Specifically, training programs have resulted in improvement on some tasks of memory and sequencing ability. Training tasks implemented with children diagnosed with ADHD (Klingberg et al., 2002; Shalev et al., 2007) or low working memory abilities (Holmes et al., 2009) as well as children with cochlear implants (Kronenberger et al., 2010) have demonstrated improvement on some cognitive tasks. These findings make it important to discover the specific skills which are delayed in children who are deaf or hard of hearing and to consider possible interventions which may reduce the variability and improve the language outcomes for all children who are deaf or hard of hearing.

Chapter II. Aims and Rationale

The aim of this study was twofold. The first goal was to substantiate group differences reported by other researchers (Conrad, 1973; Conway et al., in press; Ling, 1975; Pisoni & Geers, 2000) between children with typical hearing and children who are deaf or hard of hearing on specific tasks of memory, sequencing, and executive function. Because many of these studies measured performance on one type of task, it was necessary to determine if differences between the two groups existed across a variety of cognitive tasks. Understanding the sources of variance in speech and language outcomes is a challenging problem faced by parents, educators, audiologists, and researchers as decisions are made regarding devices and educational philosophies. Discovering the specific tasks on which children who are deaf or hard of hearing perform differently than their typically hearing peers may help identify general cognitive deficits and further inform theories about the cascading effects of auditory deprivation on other cognitive functions. In addition, once differences can be substantiated, techniques and strategies may be developed to improve skills that are delayed or deficient among this population.

The second aim of this study was to determine the effects of a visuospatial sequence training regimen on performance of tasks of phonological memory, sequencing, and executive function with children who are deaf or hard of hearing. Given that children who are deaf or hard of hearing often display poorer working memory and sequencing skills (Pisoni & Geers, 2000; Conway et al., 2011) and considering evidence that these deficits may be causally related to language outcomes (Adams & Gathercole, 1995; Conway et al., 2009), the present study proposed that implementing an adaptive visuospatial sequence training task would improve performance on a variety of cognitive tasks which may carry over to language performance. If visuospatial sequence training leads to improved sequencing or verbal performance in a research setting then it is possible these gains would result in improvements on measures of vocabulary and language ability and help to narrow the gap between children who are deaf or hard of hearing and typically hearing children.

Specifically, this study implemented a computerized, adaptive visuospatial sequence training task over 10 sessions. A sequencing task was selected because sequencing skills have been shown to underlie language acquisition. In addition it has been revealed that even tasks of short term memory result in changes in neural functioning of the prefrontal cortex, an area important for tasks of executive function (Curtis & D'Esposito, 2003; Olesen et al., 2004). Performance over time on the visuospatial sequencing task was evaluated as was performance during one pretraining and two post training assessment sessions. This allowed for comparison of the two groups prior to the start of the sessions as well as the determination of any immediate or delayed improvement.

Pre and post training cognitive measures were chosen based upon their relation to language development and academic success and included tasks of phonological memory, sequence ability, and attention and executive function. The names and descriptions of the measures are listed below:

1. The Children's Test of Nonword Repetition (CNRep; Gathercole and Baddeley, 1996) measured phonological short-term memory. This verbal test was selected because of its high correlation with vocabulary scores, language comprehension, working memory, and speech production. Links

between nonword performance and language skills have been shown to be higher and more specific than those obtained for other phonological tasks such as auditory digit span (Gathercole et al., 1994). Improvement on this task would suggest potential for growth in language skills.

2. The NEPSY-II (Korkman, Kirk, & Kemp, 1998) inhibition subtest measured the executive process of interference control or inhibition. Inhibition is controlled by the central executive, one of the main components in the Baddeley and Hitch model of working memory. This is another verbal task and improvement would indicate transfer from a visual trained task to a nontrained verbal task, a result which could have broad implications for improving language outcomes.
3. The Wide Range Assessment of Memory and Learning Second Edition (WRAML2; Sheslow & Adams, 2003) finger window task provided a measure of visuospatial short-term memory. This nonverbal task was most like the visuospatial sequencing task and was selected to determine if improvement from practice would transfer to a similar nontrained task.
4. The final assessment utilized a computerized sequence learning task to assess visual sequential memory ability. Color and black and white versions of this task allowed for comparison of improvement in sequencing ability with verbal and nonverbal stimuli. This test will be explained in greater detail in the materials and procedures section.

This study built upon some important components of previous computerized training studies. Specifically it was adaptive in nature, with sequences adjusting in length based upon subject response. Many previous training studies have demonstrated the effectiveness of adaptive training (Conway et al., 2010; Holmes et al., 2009; Thorell et al., 2009; Klingberg et al., 2002; Klingberg et al., 2005; Westerberg et al., 2007). Additionally, the visuospatial sequencing task was entirely visual. Studies which have incorporated both visual and auditory components into the training program are unable to make a clear determination regarding which method of transmission brought about an effect. Some studies providing only visual, nonverbal stimuli have reported a transfer to verbal tasks (Olesen et al., 2004; Thorell et al., 2009). Therefore, utilizing only visual stimuli in this study ensured that any effects could be attributed to the visual nature of the task. In addition, by eliminating auditory stimuli from the visuospatial sequencing task, any variability in speech or sound perception abilities among the children who were deaf or hard of hearing and in comparison to the children with normal hearing was removed as well.

Although some features were based upon prior studies, this study was unique in a number of ways as well. The first unique feature of this study was the duration of the task. Although subjects in most previous studies completed 20 or more training sessions carried out over periods of five to eight weeks, the visuospatial sequencing practice in this study took place over the course of 10 sessions in a 2 to 2 ½ week time frame (average length was 18 days; range 14 to 29 days). The 10 day practice regimen was proposed for the current study based upon the robust results of training with adults following just four days of training (Bauernschmidt et al., 2009; Conway, Bauernschmidt, Smith, & Pisoni, in preparation). A second unique characteristic of this study was that immediate and more lasting effects attributable to the visuospatial sequencing task were evaluated by testing all subjects at three separate sessions. A pretraining session took place within one week prior to the start of the first visuospatial sequencing session. The first post training assessment was given within one week of the completion of the practice sessions, and a second post training assessment session took place four to six weeks after the first post training assessment.

A final difference between this and other studies was related to its participants. This is believed to be the first study designed to improve performance through training which included both typically hearing and deaf or hard of hearing children. It was important to include both groups not only to determine differences on tasks but also to determine the effectiveness of visuospatial sequencing practice for both groups as well. Additionally characteristics of the deaf or hard of hearing subjects in this study differed from those in recent studies. Unlike the study by Kronenberger et al. (2010), the deaf or hard of hearing subjects in the present study were not exclusively cochlear implant users. Children diagnosed with a hearing loss have all experienced a period of auditory deprivation. Whether these children are ultimately fitted with hearing aids, cochlear implants, or a combination of the two devices, a period of atypical auditory input could potentially result in a cascading effect on working memory, speech, language, and even reading outcomes (Conway et al., 2009; Sharma & Dorman, 2006; Watson et al, 2007). It was therefore important to include children fitted with different types and combinations of devices and with a range of hearing loss. The children in this study who were deaf or hard of hearing can be classified into one of three groups: a group who wore two hearing aids (n = 10), a group fitted with one hearing aid and one cochlear implant (n = 11), and a group with bilateral cochlear implants (n = 11).

In summary, this study was uniquely designed to investigate possible differences in cognitive skills between children who were deaf or hard of hearing and children with typical hearing. These differences are important to determine because they may provide information about the underlying causes of poor language outcomes as well as insight into the cognitive functions which may be impacted by a period of auditory deprivation. The first hypothesis of this study was that differences between children who are deaf or hard of hearing and children with typical hearing would be revealed for a number of tasks enlisting a wide range of cognitive abilities. Significant differences were expected on verbal tasks with both auditory and visual stimuli, specifically the test of nonword repetition, the NEPSY-II inhibition task, and the sequence learning tasks with color stimuli. In addition differences were anticipated on the nonverbal visual WRAML 2 finger window sequence task. It was uncertain whether performance on the sequence learning tasks with black and white stimuli would be significantly poorer for the children who were deaf or hard of hearing.

The visuospatial sequencing task was implemented to determine any effect on the trained task as well as nontrained verbal and nonverbal measures of memory and executive function. It was important to implement this visuospatial sequencing task because improvements by children who are deaf or hard of hearing on cognitive tasks could potentially extend to the areas of speech, language, and possibly even reading. Subsequently, the potential to improve language and reading skills could have a major impact on educational techniques and strategies and ultimately on educational outcomes for all children who are deaf and hard of hearing. The second hypothesis of this study was that visuospatial sequencing practice would lead to improved performance on a variety of cognitive tasks. Specifically it was anticipated that visuospatial sequencing performance would improve for all subjects over time. In addition, it was anticipated that subjects in the adaptive condition would improve on visual and auditory tasks that were verbal in nature (nonword repetition, inhibition, and sequencing with color stimuli) as well as on nonverbal visual tasks (WRAML 2 visuospatial sequencing and sequence learning with black and white stimuli). Moreover, considering the probability that the children who are deaf or hard of hearing would demonstrate poorer performance as compared to their typically hearing peers on pretraining assessment measures, a greater benefit from visuospatial sequencing practice was expected for this group.

Chapter III. Method

Subjects

Children with typical hearing were recruited for this study from a local parochial school. The subjects who were deaf or hard of hearing were recruited from two private oral schools for the deaf in the St. Louis metropolitan area. All subjects participated on a voluntary basis. To thank the subjects for their participation and to maintain their interest, subjects were given stickers or a piece of candy following each visuospatial sequencing session and a small prize worth less than $2.00 in value upon completion of the first post training session. Inclusion criteria for the deaf or hard of hearing children consisted of the following: subjects were five to 11 years of age, diagnosed with a hearing loss at or before age three and one half, placed in a listening and spoken language educational environment, and from a primarily English-speaking environment. Children who were deaf or hard of hearing were excluded if they had any other known cognitive, motor, or sensory impairment--aside from a hearing impairment. Inclusion criteria for children with typical hearing included the following: subjects were five to 11 years of age and native speakers of English. Typically hearing children were excluded if there were any reports of cognitive, motor, sensory, or speech impairment. Children from both groups were allowed to participate in the study if parents reported that their child had a diagnosis of ADHD, and no children were excluded based upon ethnicity or socioeconomic status. The lowest age was chosen so the children could be expected to complete all assessments as well as the visuospatial sequencing task and in order to maximize the number of deaf or hard of hearing subjects that could be obtained for the study. Approximately seventy-five recruitment packets were sent home to parents at the parochial school and fifty to parents of children attending the schools for the deaf. Each packet included an informational cover letter, a brief questionnaire, and a behavioral consent form. A copy of the parent questionnaire can be found in Appendix A. This study was approved by the Human Research Protection Office (HRPO) of Washington University.

Responses were received from a total of 61 subjects, 29 with typical hearing and 32 who were deaf or hard of hearing. All met the above inclusion criteria and were therefore included in the study. According to parent reports, English was the primary language spoken in all households though four primary caretakers for the children who were deaf or hard of hearing did report fluency in another language—German, French, Hindi, and Somali. None of the caregivers reported any additional diagnosis other than ADHD for any of the subjects. For both the typically hearing and deaf or hard of hearing groups, children were age matched within their group and assigned to either control or adaptive conditions.

Typically hearing group.

Twenty-nine children with typical hearing participated in the study. Eleven subjects were male and 18 were female. Mean age for the group was 7.8 years (SD: 11.6 months, range: 6.6 to 9.7 years). At the time of training and testing 15 subjects were enrolled in first grade, eight subjects were in second grade, and six subjects were in fourth grade. None of the parents reported that their child had been diagnosed with ADHD.

Deaf or hard of hearing group.

Thirty-two children who were deaf or hard of hearing and attending one of two private oral schools in the region participated in the study. Fifteen subjects were male and 17 were female. Mean age for the group was 7.9 years (SD: 1.8 years; range: 5.3 to 11.8 years). Information regarding hearing loss was taken from parent questionnaires and provided limited general data. Etiology of hearing loss in most cases (n = 24) was reported as unknown. Four cases were reported as genetic (one hereditary of unknown origin and three due to connexin 26 genetic mutation), two as a result of ototoxic medication, one as a result of measles. One parent did not respond to this question. Age of identification ranged from birth to three and one half years of age. Severity of hearing loss was primarily profound or severe to profound (n = 21). All subjects were fitted with two devices according to the following combinations: two cochlear implants (n = 11), one cochlear implant and one hearing aid (n = 11), or two hearing aids (n = 10). For those subjects who had received cochlear implants in at least one ear (n = 22), mean age of first implantation was 3.5 years (SD: 2 years; range: 5 months to 8.7 years). According to parent reports, eight of the children in this group had been diagnosed with ADHD. Subject characteristics for this group are displayed in Appendix B.

Pre and Post Training Assessments and Procedures

Peabody Picture Vocabulary Test (PPVT 4).

The Peabody Picture Vocabulary Test 4 (Dunn & Dunn, 2007) was used as a baseline language measure prior to training, not as an assessment in the post training sessions. The PPVT 4 provides raw and standardized scores of receptive vocabulary ability for subjects ages 2:6 to 90+ years. The primary examiner administered this test to all children with typical hearing prior to the start of the pretraining assessment session.

For the subjects who were deaf or hard of hearing, PPVT 4 scores from the most recent vocabulary testing session were obtained from the assessment administrators at the schools the children attended. Children in oral schools for the deaf typically receive speech and language testing on an annual basis. Because this test is designed to be administered annually, additional testing outside of this timeframe would have been invalid. All scores obtained from subjects who were deaf or hard of hearing reflected testing that had been completed less than one year before the start of the subject's participation in the study. In all cases test administration followed the same procedure. The examiner displayed an easel with four pictures on it then said a word naming or describing one of the pictures. The subject responded by pointing to one of four picture choices or by identifying the picture by saying the number located underneath the picture. Pictures are divided into sets of 12 with all words in a particular set being presented to the subject. The test is terminated when a subject provides an incorrect response for eight of the 12 words in a given set. Raw and standard scores can be calculated.

Other assessments were used as pre and post training measures and can be categorized as verbal or nonverbal depending upon the requirement to provide a spoken response or the possibility to apply a nameable reference to the stimuli. Table 1 shows the names and category for each of the measures used in the study.

Table 1. Pretraining and post training assessments grouped by category

Verbal Assessments	Nonverbal Assessments
• NEPSY-II inhibition subtest	• WRAML 2 finger window subtest
• Children's Test of Nonword Repetition	• Sequence learning task with black and white stimuli
• Sequence learning task with color stimuli	

NEPSY-II inhibition subtest.

The NEPSY-II (Korkman, Kirk, & Kemp, 2007) is a neuropsychological assessment depicting development across a range of functional domains in children ranging from three to 16 years of age. This inhibition subtest can be considered a verbal assessment because it displays nameable objects and requires a spoken response from the subject. Designed to be administered in two or three parts depending upon the subject's age, the inhibition subtest addresses the domain of attention and executive functioning, specifically assessing the ability to inhibit automatic responses and to switch between responses. Subjects performed two or three parts of this task with two separate pages of stimuli. The first page of stimuli contained a grid of black and white shapes, as shown in Figure 1. The subject was instructed to name each shape as quickly as possible. Response time and the number of errors were recorded by the examiner. Following this naming portion of the test, subjects were instructed to go through the page of shapes again, but this time they were directed to say "circle" when they saw a square and “square” when they saw a circle. By naming the opposite shape they would be inhibiting the automatic response of the actual shape name in favor of a novel response. For subjects seven years of age or older, a third and final component of the test was administered which required performing a switching task. Subjects were instructed to say the correct name for objects that were shaded black and the opposite name for shapes that were filled in white. Following completion of the appropriate tasks with the page of circles and squares, subjects were shown a page of up and down arrows and instructed to complete the same naming, inhibition and possibly switching tasks with a response of “up” or “down”. As with the shapes, number of errors and completion time for the arrow page were recorded. Results from both pages of stimuli for each of the tasks were added together and converted into scaled scores.

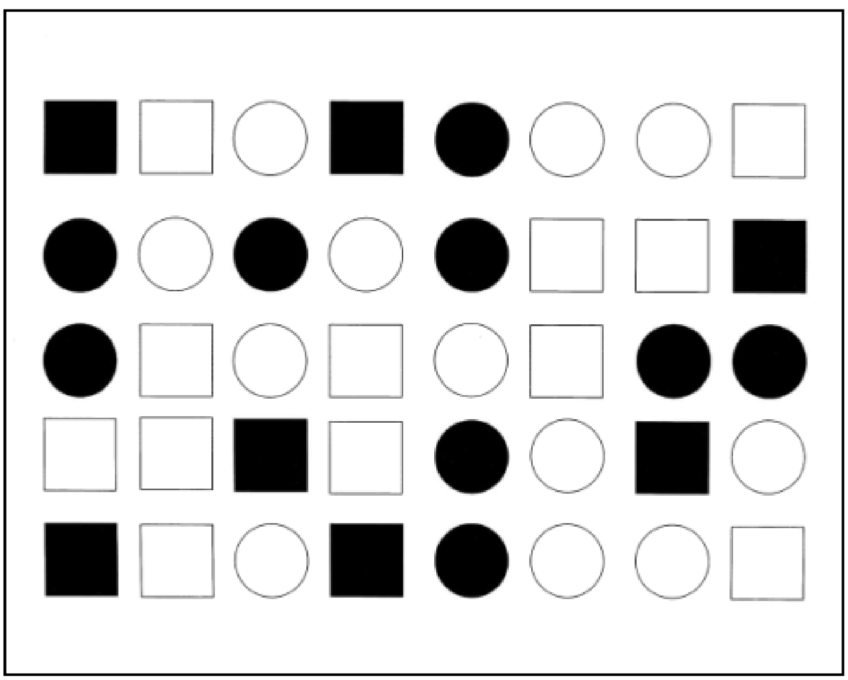

Figure 1. Shape page of the NEPSY-II inhibition subtest.

Children's Test of Nonword Repetition.

The Children's Test of Nonword Repetition (Gathercole & Baddeley, 1996) is a verbal assessment designed to measure phonological working memory in children. This task required that subjects listen to and then repeat nonsense words of varying syllable lengths. A subset of twenty words previously recorded for a study by Carter et al. (2002) and used with permission of one of that study's authors was stored on a laptop computer and presented to subjects via a loud speaker mounted on a tripod across the table from the subjects. Subjects were seated in front of the monitor facing the loud speaker. The examiner explained to the subjects that they would hear "funny" or "not real" words and instructed them to repeat back what they had heard. Two practice words and responses preceded presentation of the entire set of words to ensure that the subjects understood the task. Appendix C contains a list of the target nonwords presented in this study. Each of the twenty nonwords was presented following a tap on the touch monitor by the examiner. This manual pacing ensured that the subject had sufficient time to produce a response. The order of word presentation was randomly generated by a computer program. Responses were recorded and later transferred via W.A.S.P. (Windows Analogue Signal Processor) software to digital files and stored on the laptop computer. The responses were scored in two ways. First they were scored for overall segmental correctness, meaning they did not contain any phonological errors. Second, they were scored for syllable correctness. That is, for each nonword presented, the number of syllables produced by the subject was compared to the number of syllables presented in the target stimuli. If the numbers matched then the response was scored as having no errors. If, however, the number of syllables produced by the subject differed from the number presented in the target stimuli, the production was scored as having a syllable error.

Computerized sequence learning tasks.

A computerized visual sequence memory game, modeled after a similar task piloted with typically hearing adults (Bauernschmidt et al., 2009) and based upon the Milton Bradley "Simon" game, was selected to assess visual sequence memory ability. For this task, subjects viewed a touch-sensitive computer monitor that displayed four shapes. Similar to the Simon game, colors flashed on then off to produce a sequence which the participant was instructed to reproduce. Several different sequence learning tasks, which can be categorized as verbal and nonverbal depending upon the nature of the stimuli, were presented to the subjects on the touch screen in a 2 by 2 grid format. Based upon previous research (Dawson, et al., 2002; Parasnis et al., 1996) it is well established that verbal rehearsal can play a role in recall for items which lend themselves to verbal coding therefore sequence learning tasks that presented colored stimuli were categorized as verbal tasks.

The repeating sequence learning task with color stimuli was carried out on a touch screen monitor that displayed red, yellow, blue, and green circles on a white background as shown in Figure 2. Children were seated in front of the touch monitor and told that they were going to play a game. The test administrator tapped the screen to start a demonstration. A trial sequence of length three flashed on the touch screen. At the start of a sequence one of the four colors flashed and remained visible for 700 msec. Following the appearance of the first color, the screen was blank for a period of 500 ms after which a second stimulus appeared on the screen, again remaining visible for 700 msec. At the end of a complete sequence presentation there was a 500 msec delay, and then all four colors appeared on the screen at once along with the word “Done” displayed in a box on the monitor. The examiner replicated the computer sequence by tapping the colors to match the stimuli presented and then tapped the “Done” box to indicate that the response was complete.

Following the demonstration by the examiner, the subject was given the opportunity to attempt the task. Once again a trial sequence of length three was presented to the subject. If the subject responded incorrectly, the sequence was presented again until the correct response was given, thereby ensuring that the subject understood the task. Following successful completion of the trial sequence, a white screen appeared instructing the subject to, “Touch anywhere on the screen when you are ready.” As a subject tapped a colored circle on the touch screen in response to the stimuli, that circle flashed for 100 msec to provide visual verification of the response. A tap on the “Done” box by the subject signaled the computer to begin presentation of the next sequence. Twenty sequences were presented, beginning at a sequence length of one stimulus and increasing or decreasing in length according to a one-up, one-down design. An incorrect response to a sequence length of one resulted in the repetition of the same sequence until it was replicated correctly. For sequences two or greater in length, the sequence decreased in length by one following an incorrect response. In the repeating version of this task, a correct response on the first presentation resulted in the repetition of that first sequence along with the addition of a new stimulus. Subsequent sequences continued to build from previous presentations, increasing or decreasing in length according to the one-up, one-down rule. For example, consecutive presentations following correct responses could appear as *red, red-green, red-green-yellow* with the sequence starting over and repeating and lengthening for each successive presentation. Performance was scored as the longest sequence that was accurately replicated.

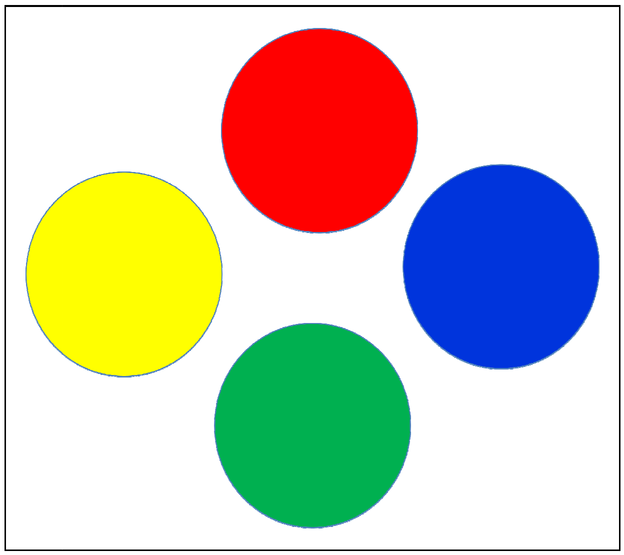

Figure 2. Sequence learning task with color stimuli

The novel sequence learning task with color stimuli followed a process similar to the repeating task in that the first sequence presented one stimulus. Following a successful response, the sequences then increased or decreased according to the one-up, one-down metric mentioned above. The key difference between the novel task and the repeating sequence learning task was that each sequence presented, whether longer or shorter, was different from the one that preceded it instead of repeating a previous sequence in lengthened or shortened form. Therefore a sample novel color sequence following correct responses might be *yellow, blue-green, red-yellow-blue.* A total of twenty sequences were again presented. As with the repeating sequence condition, correct or incorrect responses resulted in an increase or decrease by one in sequence length. Performance was scored as the longest sequence that was accurately replicated.

Two additional sequence learning tasks which utilized black and white stimuli as shown in Figure 3 were used in this study as well. In contrast to the color stimuli, the black and white stimuli do not readily lend themselves to verbal coding and as such these sequencing tasks are considered nonverbal assessments. As was the case for the color stimuli, the repeating sequence with black and white stimuli followed a one-up, one-down matrix with each longer sequence building upon previous ones. In this version, for example, one correct and one incorrect response might be represented in the pattern *lower right; lower right, upper left; lower right*, with a decrease in length from two back down to one as a consequence of an incorrect response by the subject. Again twenty sequences were presented and the score was based upon the longest sequence that was accurately replicated.

The final sequence learning task was the novel task with black and white stimuli, another nonverbal task. As with the novel sequencing task with color sitmuli, each sequence presented was new and different from the previous one, again adhering to the one-up one-down rule. Once more the longest accurate sequence produced provided the score for this task.

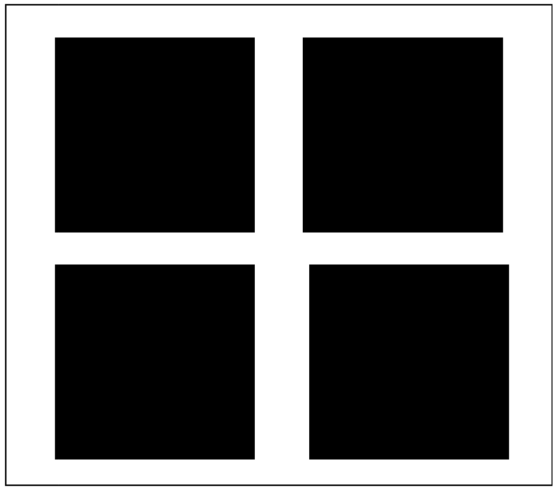

Figure 3. Sequence learning task with black and white stimuli.

The novel versus repeating versions of the sequence learning tasks potentially identify different skills. Performance on the novel sequence learning tasks required immediate recall of novel or random information. This might be considered a true measure of recall or short-term memory ability in contrast to the repeating sequence task which involves some type of learning and storage of previously presented information. Performance on the repeating sequence learning task with both color and black and white stimuli is a likely indication of implicit serial learning. Although a rule was not directly stated, subjects needed to recall a previously presented stimulus while at the same time adding new information at the end. Unlike intermittently repeated sequences which reveal the Hebb effect (Page, Cumming, Norris, Hitch, & McNeil, 2006), the sequences in this task occurred in succession. Nevertheless it is still possible that the presentation of frequently occurring sequences would reveal implicit serial learning ability.

Wide Range Assessment of Memory and Learning Second Edition.

The WRAML 2 (Sheslow & Adams, 2003) can be administered to subjects ages five through 17 and evaluates the ability for learning and memorizing information. The finger window subtest utilizes a vertically positioned card containing asymmetrically located holes to assess visuospatial memory as depicted in Figure 4. In this nonverbal task no spoken response was required; the subject's task was to replicate the actions of the examiner. Holding the template in a vertical position, the examiner poked a pencil through holes in the card one at a time to create a sequence, with pokes paced at one-second intervals. Sequences began at a length of one or three depending upon the age of the subject and increased in length throughout the course of the task according to the list provided in the test administration manual. Subjects were instructed, and shown if necessary, to use a finger to reproduce the sequence. The task was discontinued following three incorrect responses in a row. The number of sequences produced correctly was used in conjunction with the age of the subject to compute a scaled score.

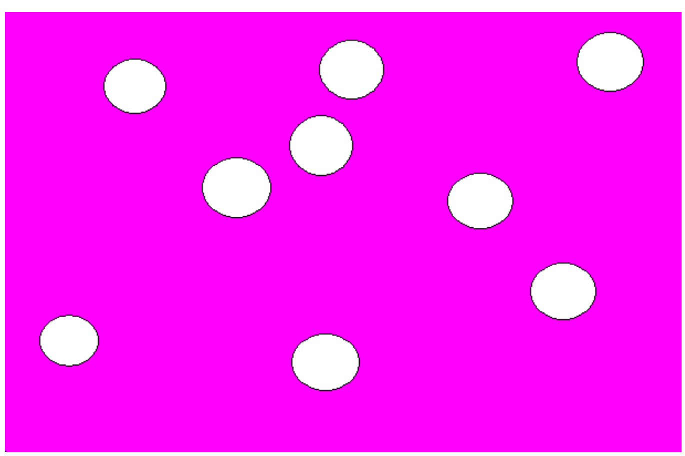

Figure 4. WRAML 2 finger window subtest template.

Equipment

All electronic-based tasks were administered via an HP 6530b laptop computer connected to a TYCO Electronics ELO TouchSystem monitor. Computer programs and data related to sequence presentation and responses were saved and later managed through an E-Prime 2.0 software program on the laptop computer. During testing and training sessions the monitors was connected to the laptop. All subject responses were made by touching the monitor and were stored in data files on the laptop.

Stimuli for the nonword test were presented through a portable loudspeaker (Anchor, Model AN-100) mounted on a tripod and positioned one meter from the child at ear level and 0^o azimuth. Wave file recordings of the speech stimuli were stored on the HP laptop and played at a level ranging from 65 to 75 dB SPL, depending upon the nonword presented, as measured by a Quest Technologies 1200 Type 2 sound level meter.

Subject responses for the nonword task were recorded through use of an Audio-Technica lavaliere microphone attached to a RANE MS1 amplifier and transferred onto digital audio tapes via a Sony DTC-75ES Digital Audio Tape Deck. Recordings were later converted into wave forms via W.A.S.P. (Windows Analogue Signal Processor) software and played back via the laptop computer for scoring purposes.

Visuospatial Sequence Training

The visuospatial sequencing task implemented in this study was modeled after one used in a previous study with typically hearing adults (Bauernschmidt et al., 2009) and carried out on a touch screen computer monitor that displayed a 4 by 4 grid of green circles as shown in Figure 5. Computer tasks which present sequences on a lighted grid and require replication through use of mouse clicks have been used in a number of working memory training studies (Holmes et al., 2009; Klingberg et al., 2005; Thorell et al., 2009; Westerber et al., 2007) Similar to those studies, subjects watched as circles flashed one at a time to present a sequence and then attempted to replicate the sequence by touching the circles on the screen in the same location and order as they were originally displayed. Circles flashed to a shade of blue when touched by the subjects in order to provide verification of their tapped response. A session consisted of 5 training sets with 30 sequences presented in each set. Completion of one session took approximately 35 minutes. Once the visuospatial sequencing regimen began, subjects continued to complete one practice session each day they attended school until ten sessions had been completed.

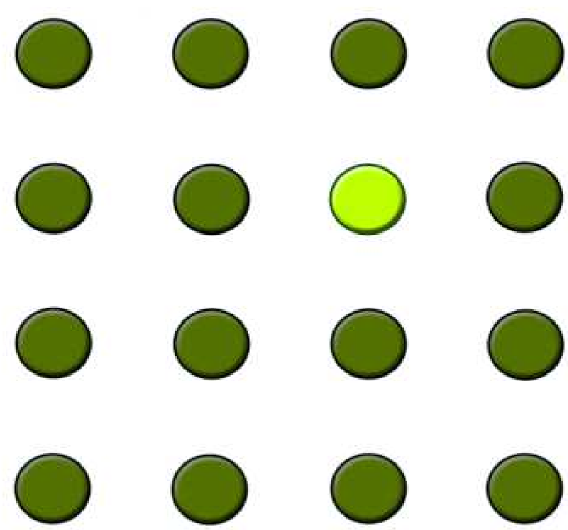

Figure 5. Touch screen display for visuospatial sequence training task.

Two separate conditions of the visuospatial sequencing task were implemented, an adaptive condition and a control condition. The importance of using an adaptive program in which the difficulty of the task matches the subject's current memory span on a trial-by-trial basis has been supported in numerous studies (Conway et al., 2010; Holmes et al., 2009; Klingber et al., 2002; Klingberg et al., 2005; Thorell et al., 2009; Westerberg et al., 2007). This technique of adjusting the difficulty level of the task automatically in order to closely approach the memory capacity of the participant has been demonstrated to produce better recall results than training with non-adaptive sequences.

In the adaptive condition and unbeknownst to the participants, the sequences shown conformed to certain underlying regularities or structure that changed on a daily basis. In the Bauernschmidt et al. (2009) study, this type of constrained and adaptive training resulted in a transfer to nontrained tasks as well as improvement on a sequence learning task, therefore it was anticipated that this design would help to maximize any effects in this study. Sequences began at a length of three with the start of each new set. As with previous working memory training studies, sequence length in the adaptive condition increased in length according to a two-up, two-down design. That is, two correct responses at a particular length resulted in a sequence length increase of one while two incorrect responses caused the sequence length to decrease by one. An incorrect response at length three resulted in the presentation of a different sequence but the length never decreased to less than three. At the end of each set of 30 sequences, a score appeared on the screen as a means of providing motivation and reinforcement to the subjects.

In contrast, sequences presented to subjects in the control groups were non-adaptive, meaning they remained at a constant length regardless of the correctness of a subject's response. The sequence began at a length of three and remained constant during each session and throughout the duration of the visuospatial sequencing regimen. In addition, the sequences were randomly generated by the computer so they did not conform to any underlying rule, with the exception that the same circle could not flash consecutively in the same position. As reinforcement and feedback, subjects were provided with a total score at the end of each block indicating the number of correct taps they had completed in response to the stimuli presented.

Schedule of Testing and Training Sessions

All assessments were administered and visuospatial sequencing sessions supervised by the primary examiner. Sessions took place in small rooms or offices with minimal distractions at the school the child was attending. Children were seated at a table on chairs or benches. For computer tasks, the touch monitors were positioned on the table at eye level and within an arm's length of the subject. For standardized tests the examiner sat next to the subjects in order to manipulate the necessary materials on the table.

Subjects were matched by age in their respective groups and divided into control and adaptive conditions prior to the start of testing and training. For the group with typical hearing, 15 subjects were assigned to the adaptive condition and 14 to the control condition. Among the children who were deaf or hard of hearing, 17 were assigned to the adaptive condition and 15 to the control condition. Device type was a blind factor in the assignment to the adaptive and control conditions. Times for testing and visuospatial sequencing sessions were arranged with teachers and school administrators so as not to interfere with instructional time in the classroom. The pre and post training assessments were administered individually to each child with breaks provided as necessary. Each testing session took between 30 and 45 minutes to complete. The same tests were used and presented in the same order in all pre and post training sessions. For each testing session the following assessments were administered:

1. Repeating sequence learning with color stimuli
2. Repeating sequence learning with black and white stimuli
3. The NEPSY II inhibition subtest
4. The nonword repetition task
5. Novel sequence learning with color stimuli
6. Novel sequence learning with black and white stimuli
7. The WRAML-2 finger window subtest

Eight children who were deaf or hard of hearing and eight in the typically hearing group did not complete the novel sequence learning tasks due to a delay in its readiness. Additionally three subjects in the deaf or hard of hearing group did not complete this task due to judgment on the part of the examiner that they were fatigued by the length of the testing session.

Visuospatial sequencing sessions were started within one week of the pretraining assessment session. Practice sessions took place each day the child attended school until 10 sessions had been completed. Two or three children were grouped together for sessions but were positioned in chairs at a table such that they could only see the touch monitor directly in front of them. Each session took between 25 and 35 minutes to complete depending upon the condition to which the child was assigned. Time for the adaptive group was generally longer than for the control group due to the potential for increased sequence lengths. Two post training assessment sessions took place upon completion of the 10 practice sessions. The first post training session took place within one week of completion to determine any immediate effect. A second post training session followed four to six weeks after the first post training session in order to determine if any effects were maintained over time.

Chapter IV. Results

Overall means and standard deviations of each of the assessment measures used in this study were calculated separately for the deaf or hard of hearing and the typical hearing groups. Descriptive statistics for each group at each training session can be found in Appendix D.1 through D.3. Appendix D.1 contains subject age at the start of the training phase of the study and both raw and standard PPVT 4 scores in addition to the assessment results.

Although the main focus of this study was to determine differences between deaf or hard of hearing and typically hearing children, analyses were also performed to determine whether the deaf or hard of hearing children differed in performance based up the type of assistive device worn. Device type and training condition information for the deaf or hard of hearing subjects is shown in Appendix D.4. Results from analyses by device type can be found in Appendix D.5.

Performance on Pretraining Assessment Measures

The first major aim of this study was to determine whether children who are deaf or hard of hearing perform differently than typically hearing peers on a variety of cognitive measures. Specifically, analyses were performed in order to determine differences between these groups in performance on pretraining assessment measures, differences in correlations between vocabulary scores and other assessment measures, and differences in performance on the visuospatial sequencing task.

A univariate analysis of variance (ANOVA) was performed on all pretraining assessment measures to determine the presence of any significant differences by hearing status. Scaled scores were calculated for subtests of the WRAML 2 and NEPSY-II tests, but no standardized or scaled scores were available for the nonword repetition test or for the sequence learning activities. Therefore analyses of these assessment measures were performed using raw scores.

Verbal assessments.

Table 2 shows the means, standard errors and t values of all tasks completed for each of the verbal assessments (PPVT 4, NEPSY-II, the Children's Test of Nonword Repetition, and the sequence learning tasks with color stimuli). For each of these assessments significant differences by hearing status emerged on at least one of the subtests. Standard scores on the PPVT 4 revealed a significant group difference, with the typically hearing group greatly outperforming the deaf or hard of hearing group, $p < .001$. The naming task of the NEPSY-II also revealed a significant difference ($p = .009$), but differences for the other tasks of this subtest did not reach significance. For the raw score assessments there were significant differences, ($p < .001$) on the nonword repetition test, both in the number of words correctly produced and the number of total syllable errors made. Additionally, significant differences were revealed for both the repeating and novel sequence learning tasks with color stimuli, both *p*s < .001.

Table 2. Pretraining Group Differences and Significances for Verbal Assessments by Hearing Status

Verbal Assessments	Deaf or Hard of Hearing		Typical Hearing		t value
	Mean	SE	Mean	SE	
PPVT 4					
Standard score	79.34	2.52	115.21	2.64	t(59) = 9.83**
NEPSY II Inhibition					
Naming task scaled score	8.83	0.59	11.33	0.70	t(49) = 2.73**
Inhibition task scaled score	8.14	0.58	9.76	0.67	t(47) = 1.83
Switching scaled score	7.88	0.64	9.09	0.77	t(25) = 1.22
Naming vs. inhibition scaled score	8.32	0.59	8.90	0.69	t(47) = 0.64
Inhibition vs. switching scaled score	7.62	0.42	8.18	0.50	t(25) = 0.85
Nonword Repetition					
Number of words correct raw score	3.09	0.52	13.18	0.56	t(58) = 13.34**
Total syllable errors raw score	4.47	0.57	0.79	0.61	t(58) = 4.39**
Sequence Learning Task					
Repeating sequence with color stimuli raw score	5.50	0.32	7.90	0.34	t(59) = 3.80*
Novel sequence with color stimuli raw score	3.90	0.25	5.05	0.24	t(39) = 2.90*

* $p < .05$. ** $p < .01$.

Nonverbal assessments.

On the nonverbal assessments (WRAML 2 and the sequence learning tasks with black and white stimuli), some significant differences by hearing status emerged as well. Performance on the WRAML 2 finger window task revealed a highly significant difference by hearing status, $p = .004$. For the repeating black and white sequence learning task, performance by the typically hearing group was significantly better than the deaf or hard of hearing group, $p = .01$, but there was not a significant difference on the novel sequence learning task with black and white stimuli, $p > .05$. These findings are presented in Table 3.

Table 3. Pretraining Group Differences and Significances for Nonverbal Assessments by Hearing Status

	Deaf or Hard of Hearing		Typical Hearing		
Nonverbal Assessments	Mean	SE	Mean	SE	t value
WRAML 2 Finger window task scaled score	9.47	0.45	11.41	0.47	t(59) = 3.01**
Sequence Learning Task Repeating sequence with black and white stimuli raw score	5.44	0.47	7.55	0.50	t(59) = 2.66**
Novel sequence with black and white stimuli raw score	4.12	0.25	4.68	0.24	t(34) = 1.43

* $p < .05$. ** $p < .01$.

Thus overall findings from the pretraining assessment session revealed a significant difference by hearing status for six of the ten verbal tasks and two of the three nonverbal tasks.

Correlations

Correlation analyses were performed in order to identify relationships between assessment measures as well as to determine if a relationship existed between receptive vocabulary ability and any of the other assessments administered in this study. Of particular interest once again was whether or not relationships were the same for both groups that participated in the study.

The first set of analyses investigated the relationship between the Peabody Picture Vocabulary Test (PPVT 4) and all other assessments. The PPVT 4 is an established language performance indicator and could thereby help to identify a potential relationship between language ability and specific tasks included in this study. For the NEPSY- II and WRAML 2 assessments which allowed for the computation of scaled scores, bivariate correlations were calculated using the PPVT 4 standard scores. Partial correlations using the raw PPVT 4 score with age entered as a covariate were computed for measures that only allowed for computation of raw scores—nonword repetition and the sequence learning tasks.

PPVT 4 correlations with verbal assessments.

For the group that was deaf or hard of hearing the PPVT 4 standard score was highly correlated with a number of verbal tasks as shown in Table 4. On the naming and inhibition tasks of the NEPSY- II the correlations were $r(28) = .37$, $p < .05$ and $r(26) = .52$, $p < .01$ respectively. There were no significant correlations for the switching, naming versus inhibition, or inhibition versus switching scaled scores of the NEPSY- II. Significant correlations were revealed between the raw PPVT 4 score and two main measures of the nonword repetition test. The number of nonwords produced correctly was highly and positively correlated with raw PPVT 4 scores, r(27) = .44, $p < .05$, whereas the correlation between raw PPVT 4 scores and total number of syllable errors was negative and significant, r(27) = -.50, $p < .01$. Raw PPVT 4 scores were thus significantly correlated with a greater number of correctly produced words and also with the production of fewer errors in replicating syllable length. Neither the repeating nor the novel sequence learning tasks with color stimuli were significantly correlated with raw PPVT scores.

Results for the group with typical hearing are shown in Table 4. No significant correlations were revealed between the standard PPVT 4 score and the scaled scores on any of the NEPSY-II verbal tasks. No correlation between the PPVT 4 and the nonword tasks were revealed. The raw PPVT 4 score did reveal a significant correlation with the verbal repeating sequence learning task with color stimuli, r(26) = .54, $p < .01$, though the difference was not significant on the novel sequence learning task with color stimuli.

Table 4. Correlation for PPVT 4 Scores and Verbal Assessments by Hearing Status

Verbal Assessments	Deaf or Hard of Hearing		Typical Hearing	
	r	*df*	*r*	*df*
NEPSY II				
Naming scaled	.374*	28	-.173	19
Inhibition scaled	523**	28	-.195	19
Switching scaled	.339	14	.408	9
Naming vs. inhibition scaled	.358	26	-.151	19
Inhibition vs. switching scaled	.020	14	.566	9
Nonword Repetition				
Number of words correct raw score	.440*	27	.203	23
Number of syllable errors raw score	-.503**	27	.115	23
Sequence Learning Task				
Repeating sequence learning with color stimuli raw score	.187	27	.543**	26
Novel sequence learning with color stimuli raw score	.119	15	-.380	16

* $p < .05$, ** $p < .01$.

PPVT 4 correlations with nonverbal assessments.

Correlations between the PPVT 4 and nonverbal tasks for the deaf or hard of hearing group are displayed in Table 5. Results revealed a significant correlation between the WRAML 2 scaled score and the standard PPVT 4 score $r(30) = .43$ $p < .05$. For the repeating and novel sequence learning tasks with black and white stimuli, raw scores were not significantly correlated with raw PPVT 4 scores.

None of the three nonverbal tasks mentioned above were significantly correlated with PPVT 4 receptive vocabulary scores for the group with typical hearing. Table 5 shows these results.

Table 5. Correlation of PPVT 4 Scores and Nonverbal Assessments by Hearing Status.

	Deaf or Hard of Hearing		Typical Hearing	
Nonverbal Assessments	*R*	*df*	*r*	*df*
WRAML 2				
Scaled score	.429*	30	-.052	27
Sequence Learning Task				
Repeating sequence learning with black and white stimuli raw score	.100	27	.346	24
Novel sequence learning with black and white stimuli raw score	.136	12	-.230	14

* p < .05. ** p < .01.

In summary, the PPVT 4 was highly correlated with one nonverbal (WRAML 2) and four verbal tasks (naming and inhibition tasks of the NEPSY-II and nonwords produced correctly and nonword syllable errors) for the subjects who were deaf or hard of hearing. Only the repeating sequence task with color stimuli was correlated with the PPVT 4 for the typically hearing group.

Correlation between all assessments.

An analysis was also performed to determine correlations between the assessments. Results are displayed in Table 6. For the deaf or hard of hearing group, the verbal nonword repetition tasks were significantly correlated with the NEPSY-II naming task, another verbal task. Interesting correlations between tasks of the sequence learning tasks emerged as well. Not surprisingly, the novel and repeating sequence learning tasks with color sitmuli, which lend themselves to verbal coding, were significantly correlated, $p < .01$. Additionally, the repeating sequence learning task with color stimuli and the repeating sequence learning task with black and white stimuli were highly correlated, $p < .01$. These repeating tasks both require subjects to retain a previous sequence in memory while adding new information. The novel sequence learning task with both color and black and white stimuli were highly correlated with each other as well, $p < .01$. Each of these novel tasks presented unique sequences at each presentation and thereby utilized short-term memory skills. Interestingly, the novel sequence learning task with color stimuli was significantly correlated, $p < .01$, with the repeating sequence learning task with black and white stimuli indicating a relationship between a short-term memory task with verbal stimuli and a repeated sequence learning task with nonverbal stimuli for this group.

Fewer significant correlations emerged for the group with typical hearing. The nonword measures of total words correct and total syllable errors were highly and negatively correlated, $p < .01$, but neither of these nonword tasks was significantly correlated with any other verbal or nonverbal assessment measures. The repeating sequence learning tasks with both color and black and white stimuli were correlated with one another, though not as highly as for the deaf or hard of hearing group, $p < .05$.

Table 6. Correlation Between all Assessments.

	Nonword words correct	Nonword syllable errors	Repeating color sequence learning	Novel color sequence learning	NEPSY naming	NEPSY inhibition	NEPSY switching	WRAML	Repeating black and white sequence learning	Novel black and white sequence learning
Nonword words correct		**-.570**	.156	.174	*.455*	.232	-.354	.253	.123	.141
Nonword syllable Errors	**-707**		-,073	-.345	**-.480**	-.198	*.528*	-.320	-.249	-.015
Repeating color sequence	.362	-.195		**.705**	.189	-.336	.244	.189	**.705**	.436
Novel color sequence	.025	-.294	.023		.403	-.318	.204	.283	**.840**	**.721**
NEPSY naming	.060	-.162	-.159	.268		.220	.280	**.557**	.086	.054
NEPSY inhibition	-.407	.362	-.356	.020	*.490*		.241	.265	-*.404*	-.173
NEPSY switching	.216	.381	-*.635*	-.293	.552	.215		.416	-.179	-.279
WRAML	-.113	.147	-.271	.357	.350	**.595**	.110		.276	.035
Repeating BW sequence	.198	.207	*.408*	.197	-.250	-.092	-.569	*.437*		**.691**
Novel BW sequence	-.203	-.183	.293	.159	-.182	-.205	-.535	.048	.060	

Deaf or hard of hearing on top right of diagonal; degrees of freedom 7 – 30.
Typical hearing on lower left of diagonal; degrees of freedom 9 – 27.
Shaded cells indicate nonverbal measures.
Note: *p < .05*. **p < .01**. Underlining indicates significance on z tests for differences between correlations at the .05 level.

Visuospatial Sequence Training Performance

Analyses were carried out to determine if performance changed significantly across the ten visuospatial sequencing sessions. An initial analysis was performed using the mean percentage of sequences that were replicated correctly each day for each subject. For this analysis performance was examined in a 2 (Hearing Status) x 2 (Training Condition) x 10 (Time) repeated measures ANOVA. Results did not reveal a significant difference or any interactions for time, training condition, or hearing status, indicating no substantial improvement on the task for either group in either condition. A significant difference for hearing status, however, was revealed, $F(1, 54) = 12.19$, $p = .001$

Performance was also scored by calculating an average daily number correct. Because sequence length did not remain constant in the adaptive condition, however, it was difficult to make comparisons in performance on the visuospatial sequencing task across the two conditions. Separate analyses were therefore performed for the adaptive and control conditions. For these analyses performance was examined in a 2 (Hearing Status) x 10 (Time) repeated measures ANOVA.

The control condition presented five sets of 30 sequences comprised of three flashes each for a total of 90 flashes in each set. The number of flashes correctly replicated for each of the five sets was averaged to obtain an average daily correct score. Results from analysis of the control condition for both the deaf and hard of hearing and typically hearing groups are displayed in Figure 6.

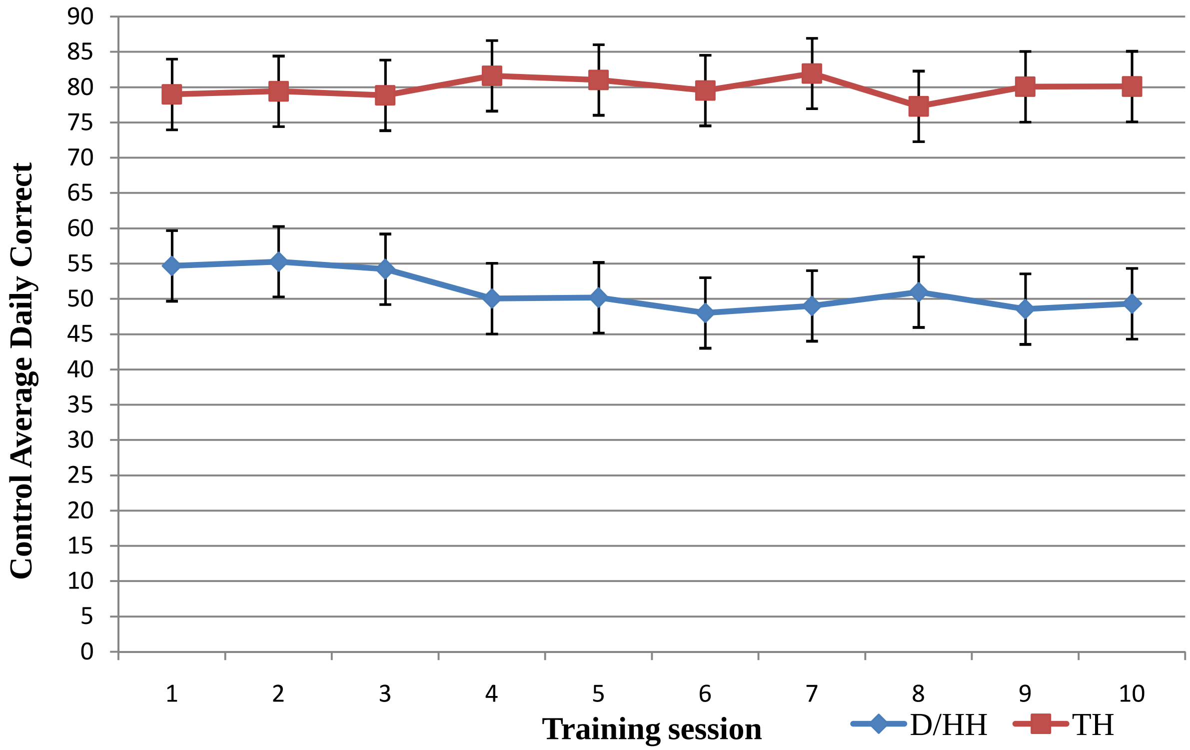

Figure 6. Control condition daily average number correct per set on the visuospatial sequence training task for deaf or hard of hearing (D/HH) and for typically hearing (TH) groups.
Error bars represent standard errors.

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As Figure 6 indicates, performance by the subjects with typical hearing remained basically flat across the visuospatial sequencing sessions while the subjects in the deaf or hard of hearing group actually showed a slight decrease in performance over time. Statistical analysis, however, revealed no significant effect for time for either group. Analysis for the control condition, however, did reveal a significant effect for hearing status, $F(1, 28) = 3.64$, $p = .003$, with the deaf or hard of hearing group performing at a significantly lower level than the group with typical hearing.

In the adaptive condition, sequence length changed in a two-up, two-down design as previously described. Thus it was possible for sequence lengths to be greater than three and for the total number of flashes per set to be greater than 90. As with the control condition, total correct responses from the five sets were used to compute a daily average number correct. Due to the differing nature of the conditions, comparisons were made between groups rather than condition. Results from the analysis of performance of both subject groups in the adaptive condition can be seen in Figure 7.

Once again the deaf or hard of hearing subjects performed at a level significantly below their typically hearing peers, $F(1,29) = 7.25$, $p < .05$. Performance over time remained low and relatively flat for the deaf or hard of hearing group. The group with typical hearing seemed to make some improvements during the first half of the sessions, with performance leveling off during the second half. The difference over time, however, was not statistically significant for either group, $p > .05$.

Performance for the adaptive group was also scored according to the longest sequence length reached each day. This highest level was averaged for subjects in both the typically hearing and deaf or hard of hearing groups. Neither grouped showed a significant increase in longest sequence length over time, but the difference by hearing status was once more present $F(1,27) = 5.44$, $p < .05$.

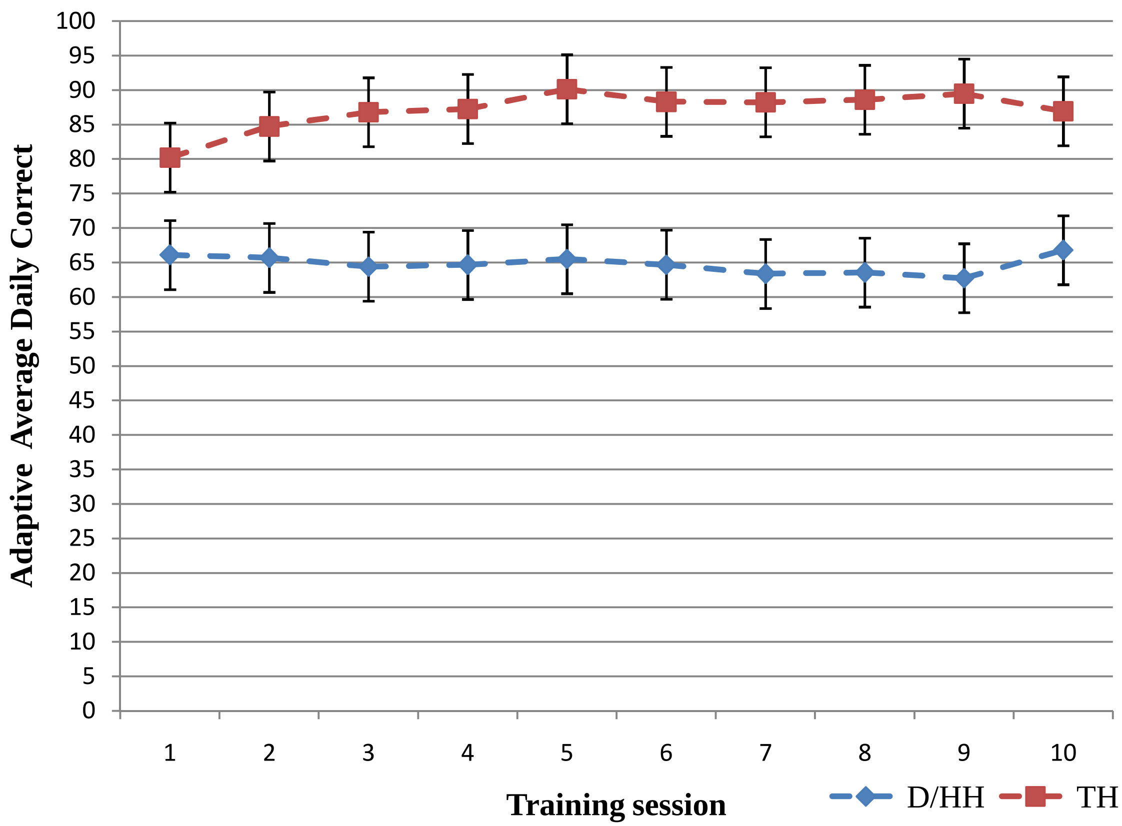

Figure 7. Adaptive condition daily average number correct per set on the visuospatial sequence training task for deaf or hard of hearing (D/HH) and typically hearing (TH) groups.
Error bars represent standard errors.

Major Effects of Visuospatial Sequence Training

The second major aim of this study was to determine whether a visuospatial sequencing regimen affected performance on a number of verbal and nonverbal tasks of memory and other executive function tasks.

Nonword repetition performance was examined in a 2 (Hearing Status) x 2 (Training Condition) x 3 (Time) repeated measures ANOVA with the last factor treated as repeated measure with unequal spacing.

Nonword repetition: number of words produced correctly.

Analysis of total number of nonwords produced correctly revealed a significant effect for time, $F(2,110) = 9.60$, $p < .001$. The number of words produced correctly by the combined groups in both conditions and at each testing session is presented in Figure 8. Performance increased from baseline (M = 8.14) to the first posttest (M = 9.21) with a little change on the second posttest ($M = 9.18$). Using Bonferroni correction, means were significantly different ($p < .05$) from pretraining to the first posttest and from pretraining to the second posttest. The figure illustrates that as a group all the subjects improved in the number of words produced correctly following the visuospatial sequencing sessions. Not surprisingly, the main effect for hearing status was also significant $F(1,55) = 221.28$, $p < .001$, with the typically hearing subjects performing better ($M = 14.00$) than the subjects who were deaf or hard of hearing ($M = 3.70$). Though not intended to display significance, the lighter shaded area on the graph represents the portion of nonwords produced correctly by the subjects who were deaf or hard of hearing and the darker shading represents typically hearing subjects.

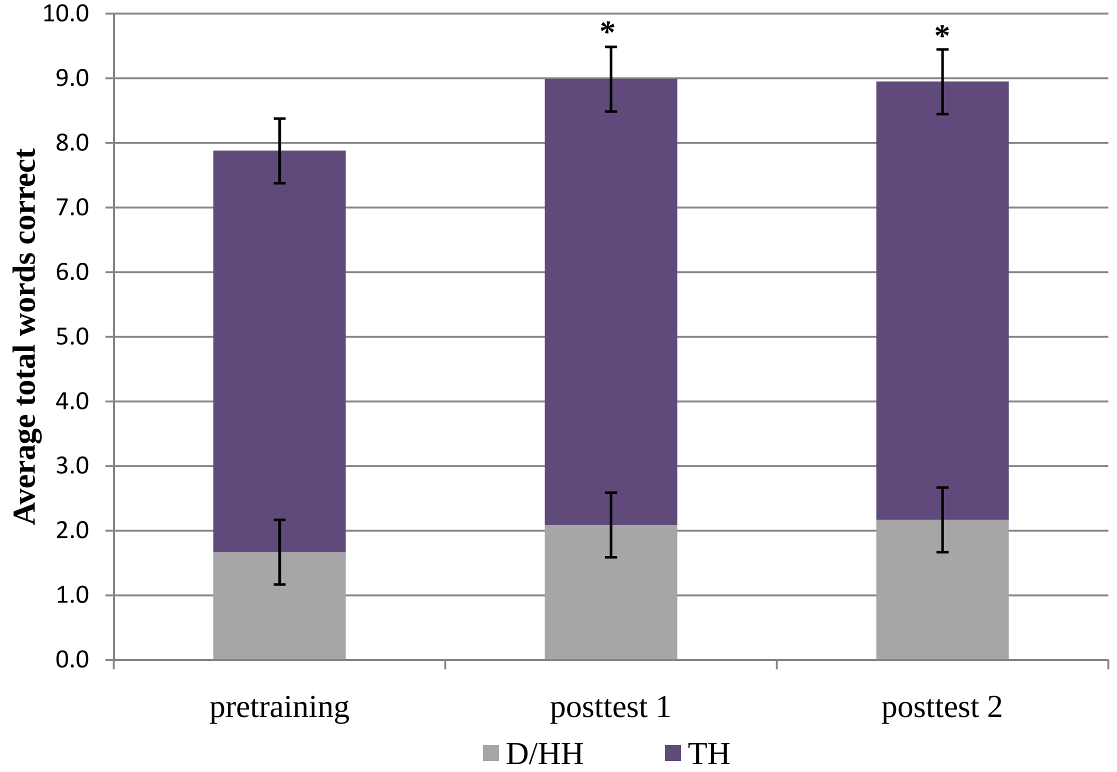

Figure 8. Number of nonwords produced correctly at pretraining, posttest 1, and posttest 2 for combined deaf or hard of hearing (D/HH) and typically hearing (TH) groups. Asterisks indicate a significant increase from pretraining to posttest 1 and from pretraining to posttest 2 for all subjects in both conditions.
Error bars represent standard errors.

Additional analyses of correctly produced words were performed at each of the 2, 3, 4, and 5 syllable lengths. Analysis of 2 syllable words produced correctly revealed a significant effect for time, $F(2, 110) = 4.04$, $p = .020$. Performance increased from baseline ($M = 2.24$) to the first posttest ($M = 2.55$) and then just slightly more to the second posttest ($M = 2.56$). The pretraining and second posttest means were significantly different using Bonferroni correction ($p < .05$). The main effect for hearing status was again significant, $F(1, 55) = 276.54$, $p < .001$. As anticipated participants with typical hearing produced more 2 syllable words correctly ($M = 3.96$) than participants who were deaf or hard of hearing ($M = 0.95$).

Analysis of 3 syllable words produced correctly revealed a significant effect for time as well, $F(2, 110) = 3.57$, $p = .031$. Performance increased from pretraining ($M = 2.61$) to the first posttest ($M = 2.94$) where it remained largely stable to the second posttest ($M = 2.92$). The first two means were significantly different using Bonferroni correction ($p < .05$). The main effect for hearing status was significant as well, $F(1, 55) = 160.88$, $p < .001$; participants with typical hearing produced more 3 syllable words correctly ($M = 4.26$) than participants who were deaf or hard of hearing ($M = 1.39$).

Analysis of 4 syllable words produced correctly revealed a different pattern of results. Although the hearing status main effect again emerged (typically hearing $M = 3.28$, deaf or hard of hearing $M = 0.68$; $F[1, 55] = 156.54$, $p < .001$), the performance over time was more complex. The Hearing Status x Training Condition x Time interaction was significant, $F(2, 110) = 4.07$, $p = .02$). As the means in Figure 9 indicate, subjects with typical hearing in the adaptive group improved their performance from baseline to both the first and second posttest sessions while the control group showed no gain from pretraining to the first posttest and decreased in the number of correctly produced 4 syllable words on the second posttest. Children who were deaf or hard of hearing in the control condition started out with poorer performance than the adaptive condition but improved by the first posttest to slightly exceed adaptive performance which showed no improvement from pretraining to the first posttest. By the second posttest subjects in the adaptive condition did show improvement, producing slightly more correct 4 syllable words than the control group. Follow-up comparisons revealed a significant difference between the control and adaptive conditions for the group with typical hearing at pretraining, $p < .05$ using Bonferroni correction; however this difference was not significant at either posttesting session. Significant differences by hearing status were present at all testing sessions, all ps < .001).

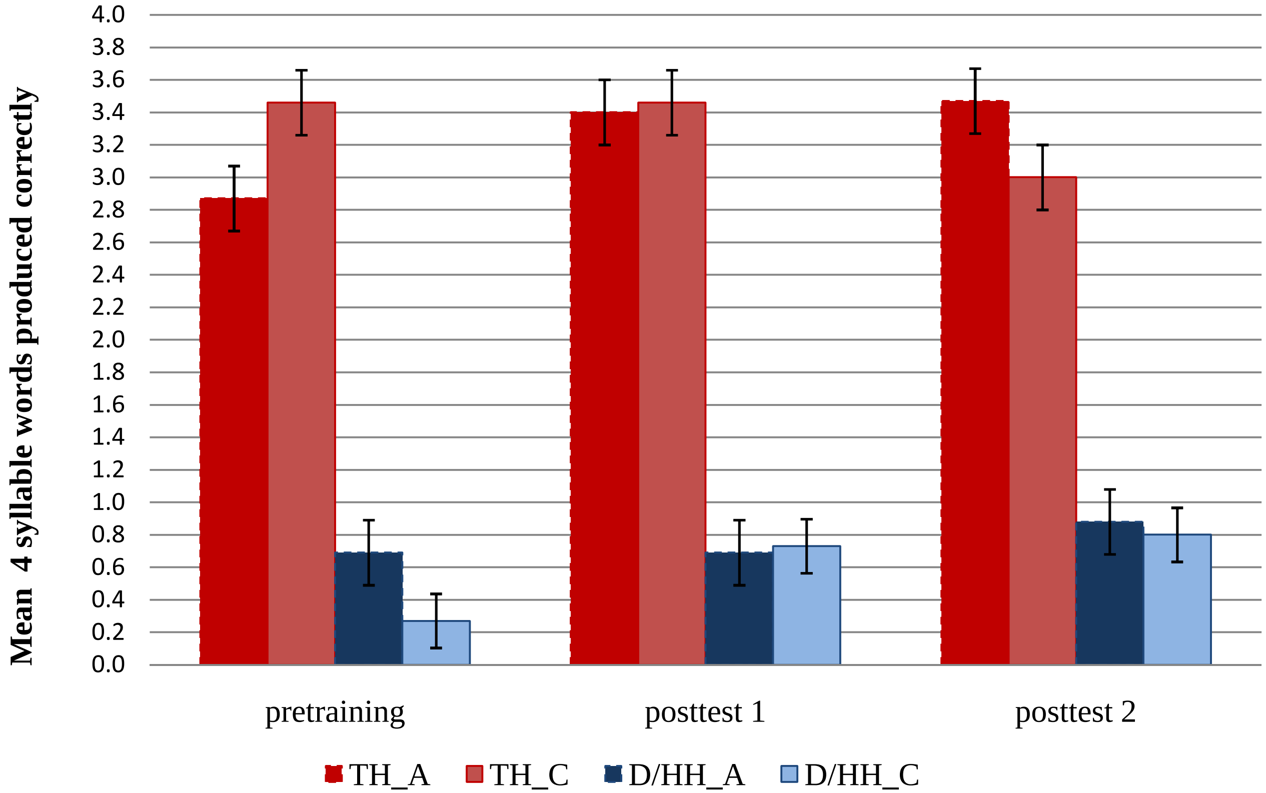

Figure 9. Mean number of 4 syllable words produced correctly at pretraining, posttest 1, and posttest 2 for Typically Hearing (TH) and Deaf or Hard of Hearing (D/HH) groups in Adaptive (A) and Control (C) conditions. Error bars represent standard errors.

Analysis of 5 syllable words produced correctly once again revealed the hearing status main effect again (typically hearing $M = 2.60$, deaf or hard of hearing $M = 0.66$; $F[1, 55] = 56.28$, $p < .001$). However no other significant results emerged.

In summary performance on the nonword task revealed significant differences by hearing status for total number of nonwords produced correctly as well as in the analyses by syllable length for each of the 2, 3, 4, and 5 syllable nonwords. The main effect for time was present for total nonwords produced correctly and for nonwords of 2 and 3 syllables in length indicating improvement following training for all subjects. All subjects in the deaf or hard of hearing group showed some improvement on the 4 syllable words. Additionally, there was a trend for the typically hearing adaptive group to improve more than the control group in the production of 4 syllable nonwords, though that increase did not reach statistical significance.

Nonword repetition: syllable errors.

In addition to calculating the number of words produced correctly, nonword performance was also analyzed for number of syllable errors made by subjects in their imitations of the target words. Because the deaf or hard of hearing group was likely to make more speech-related errors in their imitations it was thought that the number of syllables produced would be a better indicator of the ability to remember and produce nonwords of varying lengths. In addition previous research has revealed a correlation between the number of correctly produced syllables on the nonword test and performance on open-set word recognition tests and a test of auditory comprehension of language (Carter et al., 2002). An imitation was counted as a syllable error when the number of syllables produced in a subject's response did not match the number presented in the target word. A reduction in the number of syllable errors is an indication of improvement in the ability to remember and reproduce a random number of syllables and suggests a positive effect of the visuospatial sequencing practice. As with the number of words produced correctly, a repeated measures ANOVA was performed for total syllable errors. Initial analysis revealed the expected main effect for hearing status, $F(1, 55) = 18.07$, $p < .001$, with subjects who were deaf or hard of hearing making more syllable errors ($M = 3.89$) than subjects with typical hearing ($M = .50$). A significant effect for time was also revealed $F(2, 110) = 5.07$, $p = .008$ with mean total syllable errors for all subjects decreasing from the baseline ($M = 2.53$) to each posttest session (posttest 1 $M = 2.09$, posttest 2 $M = 1.96$). The difference between the pretraining and the second posttest was significant ($p < .05$) using Bonferroni correction. In addition, a significant Time x Training Condition interaction was revealed, $F(2, 110) = 3.41$, $p = .037$. As the means in Figure 10 indicate, the adaptive group produced fewer errors from pretraining to the first posttest and remained mostly stable at the second posttest while the control group basically showed no change from pretraining to the first posttest and made only slight improvement at the second posttest. Pairwise comparisons revealed that differences between pretraining and the first posttest and between the pretraining and the second posttest for the adaptive group were significant ($p < .05$ using Bonferroni correction) while no significant pairwise comparisons (Bonferroni correction ps $> .05$) emerged for the control group.

Figure 11 displays the total number of syllable errors produced by each group and in each condition. The difference between groups was significant at all three testing sessions. Although no other significant effects or interactions are presented on this graph, separation by groups shows that the reduction in syllable errors was greatest for subjects who are deaf or hard of hearing in the adaptive condition.

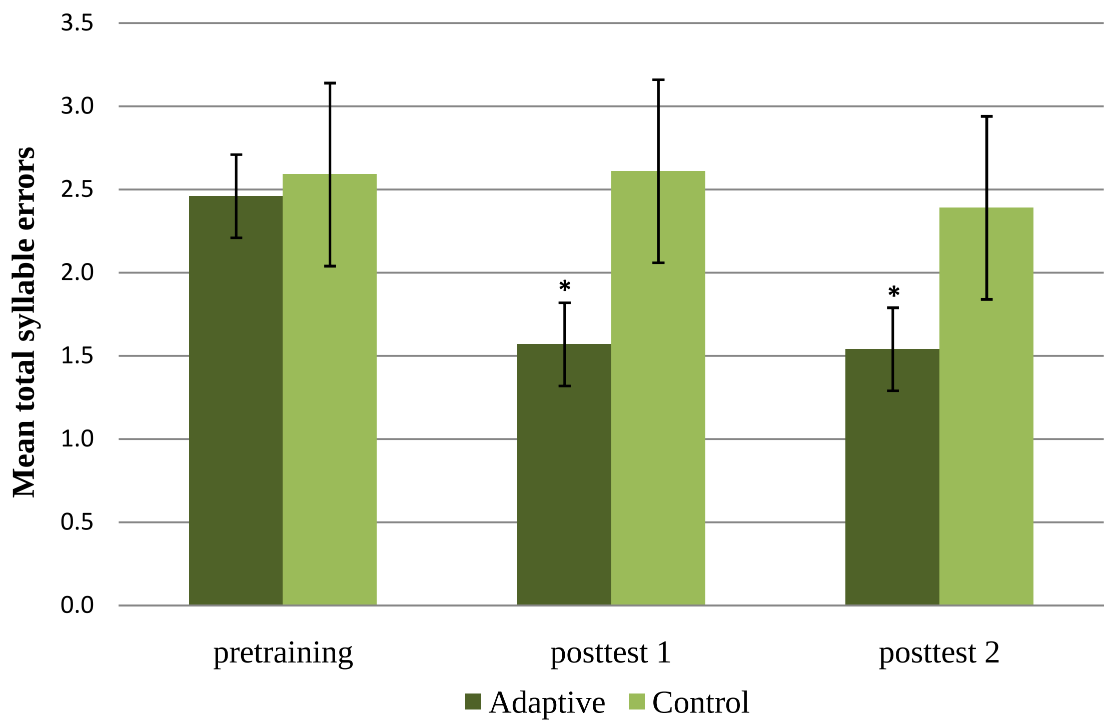

Figure 10. Mean total syllable errors at pretraining, posttest 1, and posttest 2 for combined groups in adaptive (A) and control (C) conditions. Asterisks indicate significant decreases in syllable errors from pretraining to posttest 1 and from pretraining to posttest 2 in the adaptive condition.
Error bars represent standard error

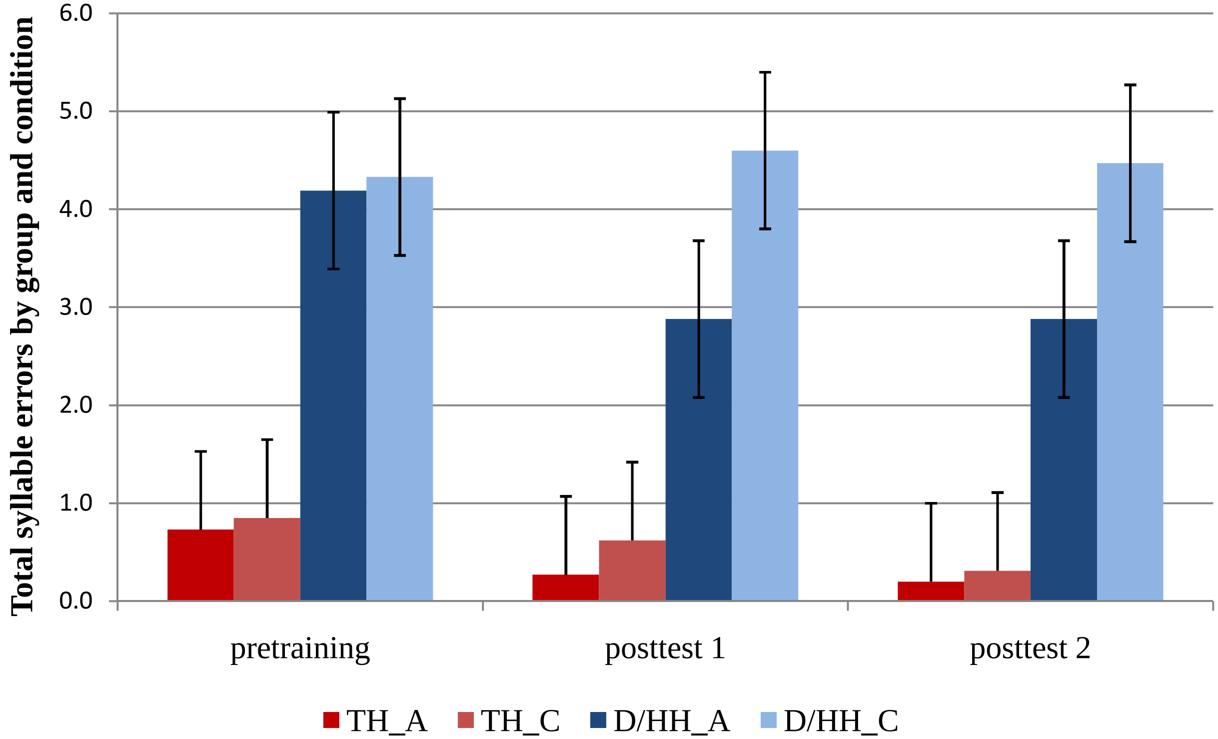

Figure 11. Mean total syllable errors at pretraining, posttest 1 and posttest 2 for Typically Hearing (TH) and deaf or hard of hearing (D/HH) groups in adaptive (A) or control (C) conditions.
Error bars represent standard errors.

As was the case for the number of nonwords produced correctly, follow up analyses for syllable errors were performed at each syllable length. The hearing status main effect was the only significant finding for 2 syllable nonwords, $F(1, 55) = 11.37$, $p = .001$, and 3 syllable nonwords, $F(1, 55) = 8.01$, $p = .05$. Consistent with previous syllable error analyses, the 4 syllable nonword analysis showed the hearing status difference, $F(1, 55) = 113.03$, $p = .001$. In addition, a Time x Training Condition was revealed, $F(2, 110) = 6.28$, $p = .003$. Figure 12 illustrates that the mean number of syllable errors for 4 syllable words decreased across testing sessions for subjects in the adaptive condition (pretraining $M = .76$, posttest 1 $M = .44$, posttest 2 $M = .38$) with pairwise comparisons revealing a significant difference between pretraining and the second posttest ($p < .05$) using Bonferroni correction.

Figure 13 shows the mean number of syllable errors for 4 syllable nonwords by each group in each condition. As previously stated there was a significant difference between groups at all three testing sessions. Although no other significant effects or interactions are presented on this graph, separation by groups illustrates that the reduction in syllable errors for 4 syllable words is greatest for deaf or hard of hearing subjects in the adaptive condition.

Analysis of the syllable errors for nonwords 5 syllables in length only revealed the main effect of hearing status, $F(1, 55) = 21.12$, $p < .001$.

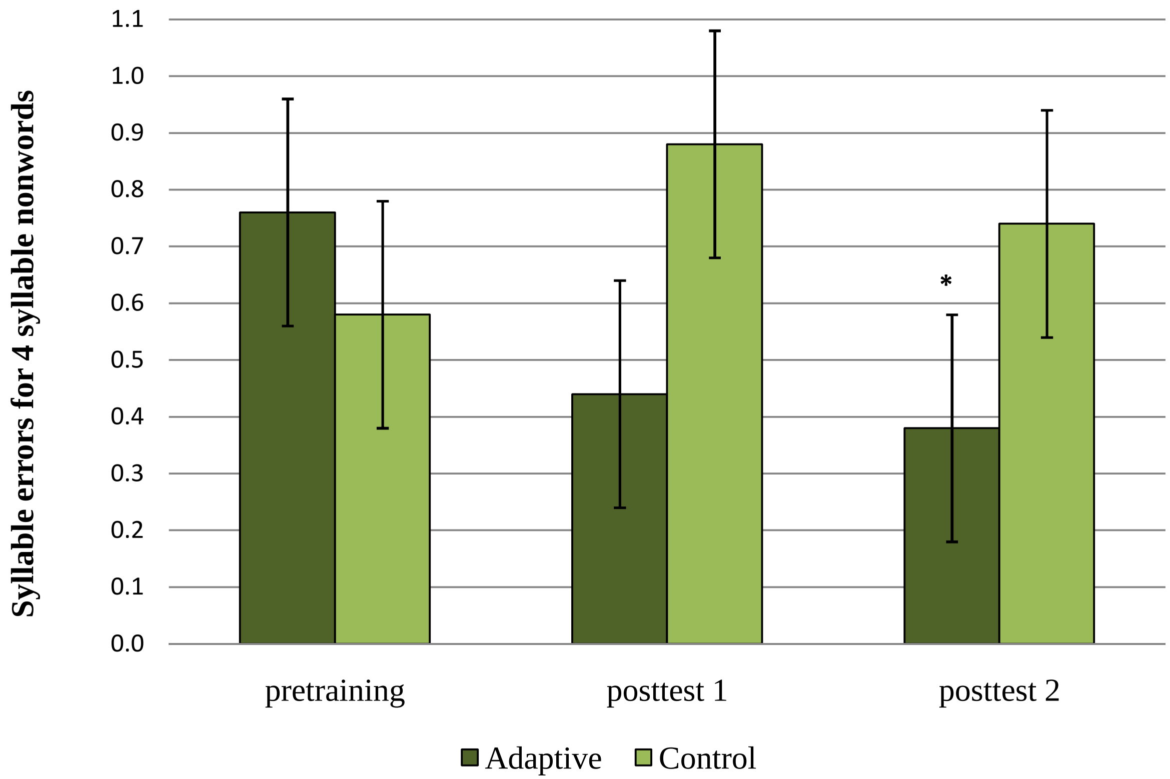

Figure 12. Mean number of syllable errors for 4 syllable nonwords at pretraining, posttest 1, and posttest 2 for combined groups in adaptive and control conditions. The asterisk indicates a significant decrease in syllable errors from pretraining to posttest 2 in the adaptive condition.
Error bars represent standard errors.

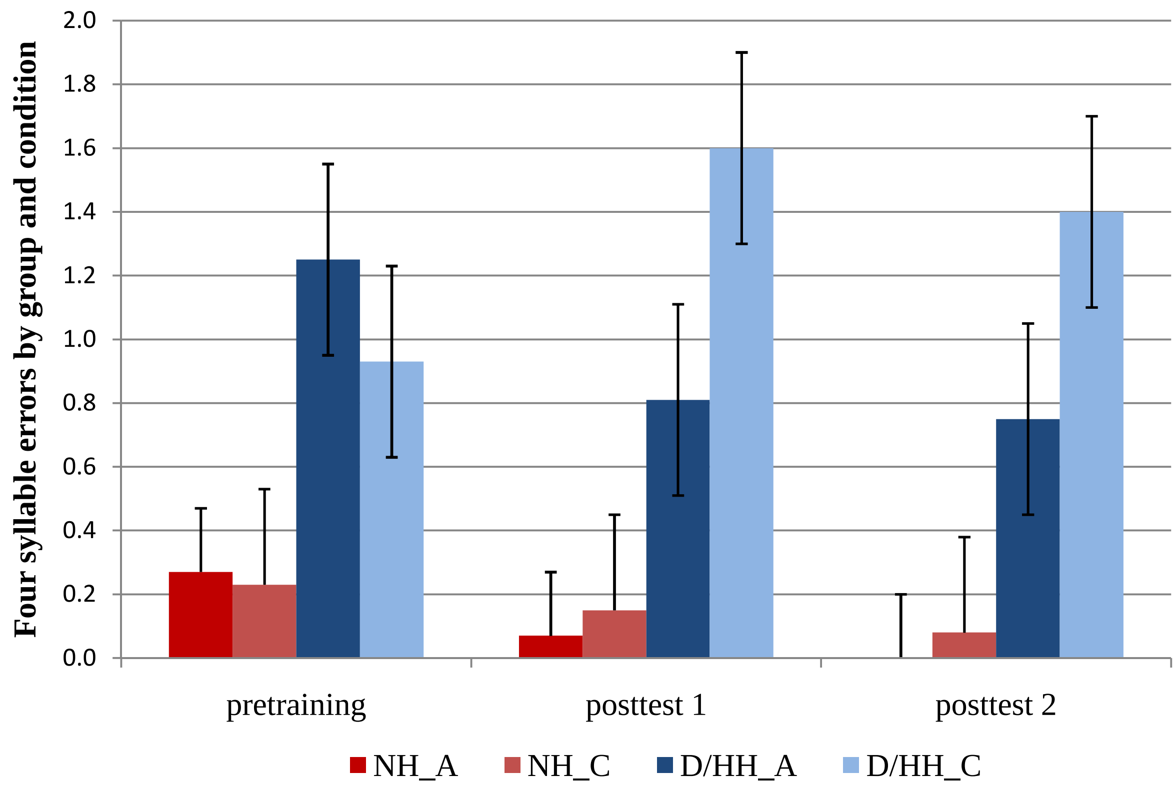

Figure 13. Mean number of syllable errors for 4 syllable nonwords at pretraining, posttest 1 and posttest 2 for typically hearing (TH) and deaf or hard of hearing (D/HH) groups in adaptive (A) and control (C) conditions.
Error bars represent standard errors.

To summarize the analysis of nonword syllable errors, a hearing status effect was revealed for total syllable errors as well as for syllable errors for the 2, 3, 4, and 5 syllable nonwords. Additionally, an effect by condition for total syllable errors and for syllable errors in 4 syllable nonwords was revealed. Subjects in the adaptive condition produced fewer errors than subjects in the control group following visuospatial sequencing practice.

Thus on the nonword repetition task a significant difference for hearing status emerged on all tasks. A significant effect for time was also revealed for total nonwords correctly produced and for production of nonwords 2 and 3 syllables in length. For 4 syllable nonwords a Hearing Status x Training Condition x Time interaction occurred. When syllable errors were analyzed, a significant effect for condition was revealed for the total number of syllable errors produced and the syllable errors for 4 syllable nonwords. The significant findings are indications of improved performance on tasks of phonological memory following visuospatial sequencing practice.

Minor Effects of Visuospatial Sequence Training

Sequence learning tasks with color stimuli.

Performance on all versions of the sequence learning tasks was also examined in a 2 (Hearing Status) x 2 (Training Condition) x 3 (Time) repeated measures ANOVA with the last factor treated as repeated measure with unequal spacing.

The repeating sequence learning task with color stimuli required repetition of colored sequences that repeated and built in length based upon correct reproductions. Performance was scored according to the length of the longest sequence correctly produced by the subject. In addition to a hearing status main effect, $F(1, 56) = 19.66$, p

$<.001$, a significant Hearing Status x Time x Training Condition interaction emerged, $F(2, 112) = 3.17$, $p = .046$. The means in Figure 14 illustrate a significant improvement as verified by pairwise comparison for the typically hearing control group from pretraining to the first posttest as well as from pretraining to the second posttest ($p < .05$). Additional pairwise comparisons revealed a significant difference between the adaptive groups based on hearing status at pretraining ($p <.05$), but a decline in performance by the typically hearing group resulted in a nonsignificant difference at the first and second posttests, $p > 05$. For the control condition, differences between subjects with typical hearing and those who were deaf or hard of hearing were significant for all three time periods ($p< .05$ using Bonferroni correction).

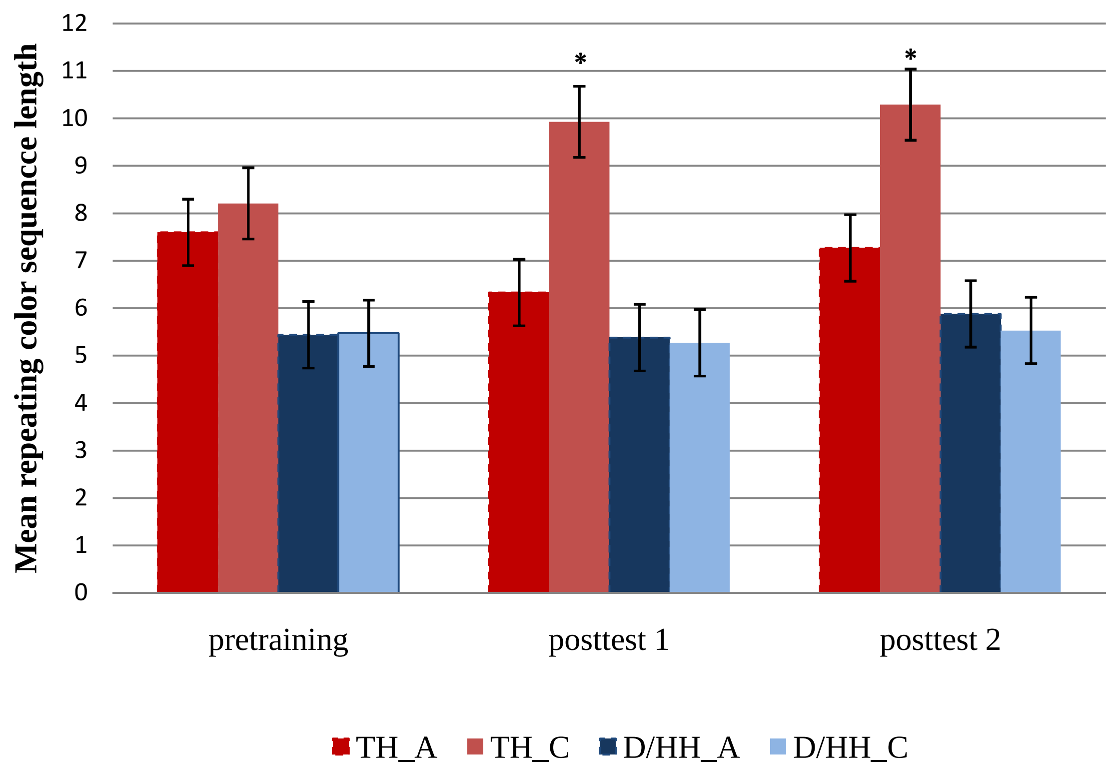

Figure 14. Mean longest sequence length for repeating sequence learning task with color stimuli for typically hearing (TH) and deaf or hard of hearing (D/HH) groups in adaptive (A) and control (C) conditions at pretraining, posttest 1 and posttest 2. Asterisks indicate a significant increase in mean sequence length from pretraining to posttest 1 and from pretraining to posttest 2 for typically hearing group in the control condition.
Error bars represent standard errors.

A similar result was revealed for the novel sequence learning task with color stimuli that presented a unique yet increasingly longer sequence following each correct response. The results are illustrated in Figure 15. The main effect for hearing status, $F(1, 37) = 15.11$, $p < .001$, was again present. In addition a significant Time x Hearing Status x Training Condition interaction appeared, $F(2,74) = 4.26$, $p < .05$. Differences in mean sequence length did not significantly improve across testing sessions for either the deaf or hard of hearing group or the group with typical hearing in either the control or the adaptive conditions. Pairwise comparisons, however, did reveal a significant difference by hearing status for the adaptive condition at pretraining ($p < .05$) which did not remain significant at either posttest session (*p*s >.05). This appears to be the result of slightly poorer performance by the typically hearing group in conjunction with slightly better performance by the deaf or hard of hearing group across time. (TH pretraining $M = 5.18$, posttest 1 $M = 4.55$, posttest 2 $M = 4.82$; D/HH pretraining $M = 3.73$, posttest 1 $M = 4.09$, posttest 2 $M = 4.18$) Conversely, a difference by hearing status for the control condition was not significant at pretraining ($p > .05$) but did reach significance for each posttesting session ($p < .001$, $p < .05$ respectively). Another unique pattern was revealed with the typically hearing controls improving from pretraining to the first posttest and then dropping very slightly while the deaf or hard of hearing controls performed more poorly at the first posttest compared to the pretraining session and then nearly rebounded to their original level at the second posttest (TH pretraining $M = 4.90$, posttest 1 $M = 5.30$, posttest 2 $M = 5.10$; D/HH pretraining $M = 4.11$, posttest 1 $M = 3.33$, posttest 2 $M = 4.00$).

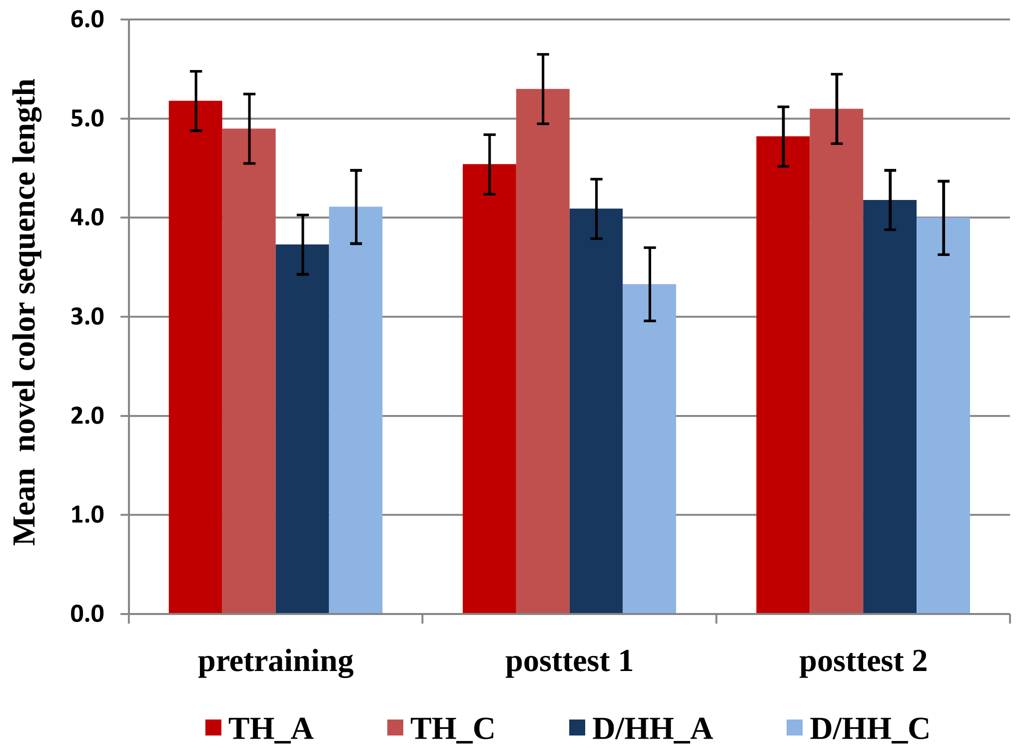

Figure 15. Mean sequence length for the novel sequence learning task with color stimuli for typically hearing (TH) and deaf or hard of hearing (D/HH) groups in adaptive (A) and control (C) conditions at pretraining, posttest 1, and posttest 2.
Error bars represent standard errors.

NEPSY- II.

As with previous measures, performance on the NEPSY- II inhibition subtest was examined in a 2 (Hearing Status) x 2 (Training Condition) x 3 (Time) repeated measures ANOVA with the last factor treated as repeated measure with unequal spacing. As described in the methods section, the test was comprised of 2 or 3 tasks (depending upon subject age) with 2 sets of stimuli. Scaled scores for each task as well as combined scaled scores were calculated. Scaled score performance for the naming task revealed the expected significant main effect for hearing status $F(1, 46) = 9.31$, $p < .05$ with typically hearing subjects performing better than the deaf or hard of hearing group, but no other significant results were revealed. However, on the inhibition task which requires subjects to name the opposite shape of the one displayed, a significant effect for time emerged $F(1, 43) = 30.72$, $p < .001$ in addition to the significant difference by hearing status $F(1, 43) = 4.48$, $p < .05$. Performance on the inhibition task increased from pretraining $M = 8.74$ to the first posttest $M = 11.14$ and slightly more at the second posttest $M = 11.63$. Using Bonferroni correction, the differences between pretraining and the first posttest as well as for pretraining and the second posttest were significant, both *p*s < .001.

The naming versus inhibition scaled score uses scaled scores from each individual task to form a combined scale score. It is not surprising then that this score also revealed some significant effects. Once again a main effect for time appeared $F(2, 86) = 17.76$, $p < .001$. Scaled scores for this combined score improved from pretraining $M = 8.43$ to the first posttest $M = 10.99$ and even more by the second posttest $M = 11.45$. The differences between pretraining and posttest 1 as well as pretraining and posttest 2 were significant, *p*

< .001, using Bonferroni correction. For this score, however, the effect for hearing status was not significant, $p > .05$.

The switching task of the NEPSY-II inhibition subtest required subjects to make different responses depending upon the color of each item named. On this task there was no significant effect for hearing status but the main effect for time again emerged $F(2, 42) = 13.44$, $p < .001$. The improvement in performance mirrored that of the inhibition task in that the mean increased from pretraining $M = 8.22$ to the first posttest $M = 11.12$ and remained fairly stable at the second posttest $M = 11.18$. Using Bonferroni correction, the differences between pretraining and the first posttest as well as for pretraining and the second posttest were significant, both ps < .001.

The final NEPSY-II scaled score was another combined score, inhibition versus switching, and significant effects were revealed for both time $F(2, 38) = 16.06$, $p < .001$ as well as hearing status $F(1, 19) = 16.96$, $p < .05$. In addition a Time x Hearing Status effect also emerged $F(2, 38) = 9.90$, $p < .001$. Figure 16 illustrates the increase in mean scaled score by the typically hearing group from pretraining to posttest 1 followed by a very slight decline from that level to posttest 2. Pairwise comparisons revealed the difference between pretraining and the first posttest as well as between pretraining and the second posttest to be significant (both ps < .05) using Bonferroni correction. The deaf or hard of hearing group made only a very slight increase from pretraining to posttest 1 and stayed at that same level for posttest 2.

Figure 17 shows the inhibition versus switching scaled scores for each group in each condition at each of the assessment sessions. No statistically significant interactions emerged, yet a steady improvement for deaf or hard of hearing subjects in the adaptive condition can be seen.

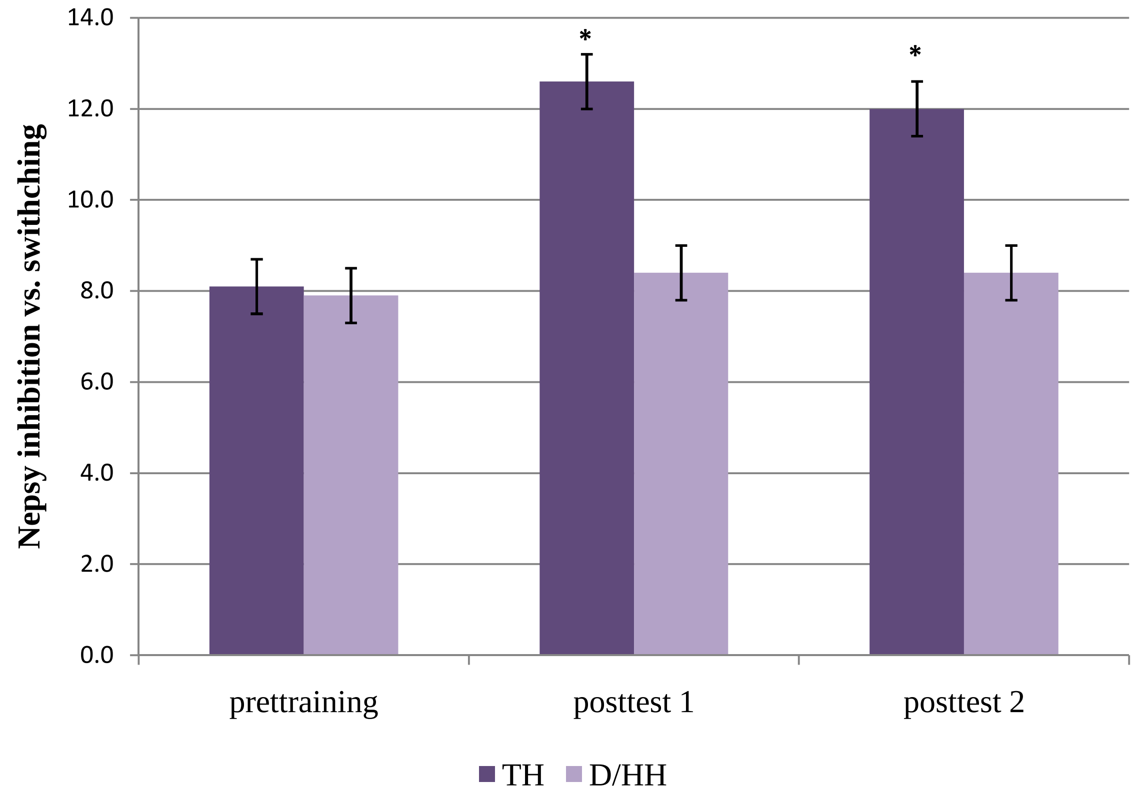

Figure 16. NEPSY- II inhibition versus switching mean scaled score for the deaf or hard of hearing (D/HH) and typically hearing (TH) groups at pretraining, posttest 1 and posttest 2 sessions. Asterisks indicate a significant improvement from pretraining to posttest 1 and from pretraining to posttest 2 for the typically hearing group. Error bars represent standard errors.

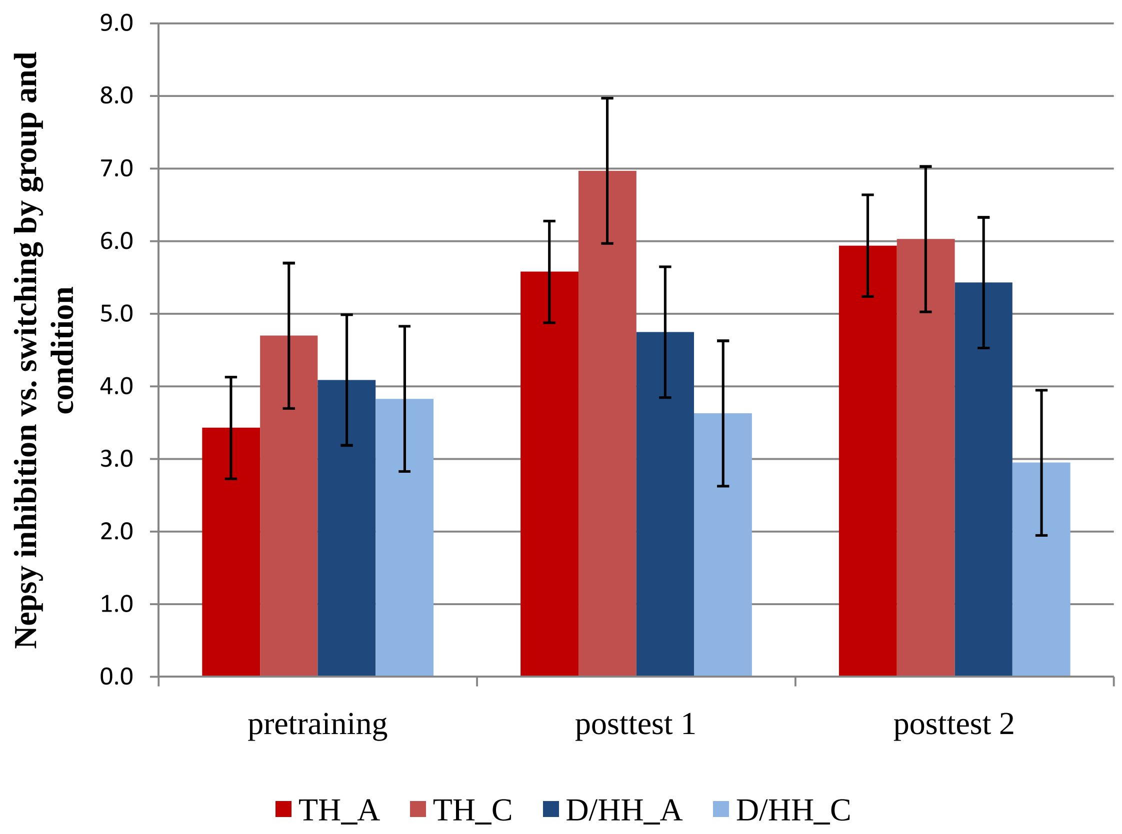

Figure 17. NEPSY-II inhibition versus switching mean scaled score for typically hearing (TH) and deaf or hard of hearing (D/HH) groups in adaptive (A) and control (C) conditions.
Error bars represent standard errors.

Overall results for the NEPSY- II indicated an effect for hearing status on three of the five scaled scores. Neither the naming versus inhibition nor the switching scores revealed a hearing status effect. There was, however an effect for time on all of the tasks except the naming task. Additionally, a Time x Hearing Status effect emerged on the inhibition versus switching score with the typically hearing group performing better and improving more over time than their peers who were deaf or hard of hearing.

WRAML 2.

The nonverbal WRAML 2 finger window task required subjects to poke a finger through holes in a template to copy sequences produced by the examiner. The same analysis design used with previous measures was employed with the WRAML 2 subtest. Results revealed the predictable hearing status effect, $F(1, 56) = 15.51$, $p < .05$, but a significant effect for time was also revealed, $F(2, 112) = 4.08$, $p =. 019$. Performance increased from the pretraining baseline ($M = 10.38$) to the first posttest ($M = 11.07$) and decreased very slightly on the second posttest ($M = 11.02$). The means for the pretraining and the first posttest were significantly different using Bonferroni correction ($p < .05$).

Sequencing learning tasks with black and white stimuli.

The repeating sequence learning task with black and white stimuli only revealed a significant effect for hearing status $F(1, 56)$, $p < .001$. No significant effects, including that of hearing status, emerged for the novel sequence learning task with black and white stimuli.

Thus for nonverbal tests, there was a significant difference between the subjects who were deaf or hard of hearing on two of the three tasks (WRAML 2 and repeating sequence learning with black and white stimuli) as well as an effect for time on the inhibition, the naming versus inhibition, and the switching tasks of the NEPSY-II and the WRAML 2 finger window task following training.

Chapter V. Discussion

Technological advances in hearing aids and cochlear implants have provided children who are deaf or hard of hearing with earlier and better access to sound. Despite these advances, however, many children with a hearing loss continue to perform at levels below their typically hearing peers on measures of language and reading ability. Intrinsic factors such as IQ, etiology, and the presence of additional disabilities along with treatment components including age of identification, early intervention services, and mode of communication have been identified as contributing factors to this disparity (Geers et al., 2007). Yet even after controlling for these factors, there remains a large amount of variance that may be related to processing mechanisms which encode, store, retrieve, and rehearse the phonological components of spoken words (Pisoni, 1999). Evidence indicates that a period of early auditory deprivation results in atypical development of the auditory system (Sharma and Dorman, 2006). Furthermore, normal development of the auditory pathways is generally accepted as a precursor to normal development of speech and language skills (Sharma, Tobey, Dorman, Bharadwaj, Martin, Gilley, & Kunkel, 2004). Sound, with its sequential and temporal nature, may therefore provide the medium through which more general cognitive abilities related to or dependent upon sequential or temporal patterns are developed. In fact a number of studies have revealed poor sequencing or implicit learning abilities among children who are deaf or hard of hearing (Conway et al., 2011; Furth & Pufall, 1966; O'Connor & Hermelin, 1973) as well as varying degrees of performance related to the age of implantation (Johnson & Goswami, 2010). Additionally, significant correlations have been revealed between visual sequencing tasks and measures of spoken language

(Conway et al., 2011) and reading comprehension (Johnson & Goswami, 2010). These results lend support to the auditory scaffolding theory proposed by Conway et al. (2009) and findings by Watson et al. (2007) that lack of early auditory stimulation has a cascading effect on a variety of perceptual and cognitive processes beyond those related to audition. Identifying some of the specific abilities impacted by a period of auditory deprivation, therefore, becomes paramount as researchers and teachers of the deaf seek to gain a better understanding of the variability in abilities among children who are deaf or hard of hearing in order to improve language outcomes for this population.

As previously noted, several important features from prior studies were incorporated into the design of this study. The visuospatial sequencing task was entirely visual in nature so that performance would not be affected by variability in sound perception by the subjects. In addition the task was adaptive in order to maximize its effectiveness. A number of elements were unique to this study as well. First of all, the length of the visuospatial sequencing regimen was somewhat unique. Subjects participated in sessions for ten days which was relatively short in comparison with many previous studies. As a second unique characteristic of this study, posttesting was performed at two time periods, the first within one week of the tenth session and a second four to six weeks later. These two sessions were selected to provide information regarding short-term and more enduring effects. The group of participants contributed to the third unique element of this study. It is believed that this is the first study to implement a visuospatial sequencing task with children who were deaf or hard of hearing as well as children with typical hearing. Additionally, deaf or hard of hearing subjects fitted with various devices and combinations of device types were included. All children who are deaf or hard of hearing experience a period of early auditory deprivation which may reduce their temporal pattern experience and subsequently impact sequencing and language skills (Conway et al., 2011; Furth & Pufall, 1966; O'Connor & Hermelin, 1973; Johnson & Goswami, 2010). It was therefore important to include children who wore hearing aids, those fitted with a hearing aid and a cochlear implant, and those with bilateral implants.

A final important factor of this study involved the assessment tools selected. These assessments were chosen to measure a wide range of cognitive abilities representing components of spatial, sequence, visual, and verbal memory ability as well as the executive function task of inhibition. Results from neuroimaging studies have provided evidence that training on visuospatial tasks leads to increased prefrontal cortex activity (Curtis & D'Esposito, 2003; Olesen et al., 2004), and behavioral studies have shown a transfer to tasks involving verbal memory or executive processing (Kronenberger et al., 2010; Thorell et al., 2009). Moreover, working memory is related to language development (Adams & Gathercole, 2000). It was therefore important to include several types of tasks in order to determine any specific abilities that may be improved by visuospatial sequencing practice.

Performance Differences Between Groups

The first major aim of this study was to substantiate differences between subjects who were deaf or hard of hearing and subjects with typical hearing on a variety of cognitive tasks. It was hypothesized that a difference by hearing status would be revealed on a variety of verbal and noverbal tasks, and results verified this hypothesis. Results from all pretraining assessments can be seen in Appendix D.1. Not surprisingly, differences on the Peabody Picture Vocabulary Test (PPVT 4) were significant with average scores for the children who were deaf or hard of hearing falling more than two standard deviations below the mean. Additional analyses shown in Table 2 revealed significant differences between the deaf or hard of hearing and typically hearing groups for at least one task of each of the verbal assessments.

The NEPSY-II inhibition subtest is considered a verbal task because a spoken response to visual stimuli is required. As previously described, the subtest is comprised of up to three different tasks: naming, inhibition, and switching. A significant difference was revealed between the groups on the naming task which required subjects to name shapes or arrow directions presented in rows across a page as quickly as possible. With a mean scaled score of 8.66, subjects who were deaf or hard of hearing performed this task much more slowly and with many more errors than the subjects with typical hearing whose mean scaled score was 11.33. A scaled score of 10, as explained in the NEPSY-II Clinical and Interpretive Manual (Korkman et al, 2007), represents mean performance within a given age group. Lower scores on the naming task are indicative of a problem with naming, poor self-monitoring, slow psychomotor speed, or difficulty accessing semantic information. These difficulties were apparent for the subjects who were deaf or hard of hearing as the examiner observed many of these subjects proceeding slowly and deliberately as they named each shape. Presumably the process involved retrieving the proper label followed by the task of connecting speech sounds to produce the correct word to match each shape. For subjects with typical hearing the naming task appeared to be much more automatic and relatively effortless.

The difference between groups was not significant on the inhibition or switching tasks of the NEPSY-II test, however. Low performance on these tasks indicates impulsivity or slow processing speed resulting from the inhibitory or switching demands of the tasks. Scaled scores for the subjects with typical hearing dropped below the mean on these tasks. The deaf or hard of hearing subjects, however, appeared to be less impacted by the additional cognitive load associated with these tasks than the typically hearing group, with their mean scaled score remaining in the same range as their naming score (low average). Subjects who do not have a strong link between the visual stimuli and its verbal description are likely to be less impacted by the additional inhibitory requirement (Korkman et al., 2007). The low performance by subjects who were deaf or hard of hearing on the naming task indicates a problem accessing semantic information resulting in reduced automaticity in naming familiar objects and potentially impacting language development. This reduced automaticity may help to explain why subjects who were deaf or hard of hearing did not show a greater decline in performance when the inhibitory requirement was added. In addition a struggle with such a basic language task offers possible insight into other cognitive difficulties displayed by children who are deaf or hard of hearing. As Bebko and McKinnon (1990) noted in their study, an incomplete mastery of language may lead to the ineffective use of cognitive strategies and possible effects on language and reading ability.

. On the next verbal measure, stimuli from the Children's Test of Nonword Repetition, differences between the groups were anticipated and observed for accuracy of production and matched syllable length. However, several interesting findings and similarities among the groups emerged as well. Each group produced more 3 syllable nonwords correctly than nonwords that were 2, 4, or 5 syllables in length. It is probable that 3 syllables represent an optimum length, providing more acoustical and phonological information than the shorter 2 syllable nonwords yet not taxing memory capabilities as much as the 4 and 5 syllable stimuli. Additionally, deaf or hard of hearing and typically hearing subjects were both more likely to produce an incorrect number of syllables in their response as the syllable length of the nonword increased. This is also indicative of an increased load on memory and imitative ability for both groups. Although overall performance by the deaf or hard of hearing subjects was significantly below that of the typically hearing subjects, these similar trends coupled with the significant correlation between nonword repetition and receptive vocabulary as measured by the PPVT 4 for the deaf or hard of hearing subjects suggest that improvement in nonword abilities by the deaf or hard of hearing group may lead to improved receptive and expressive vocabulary skill.

The final verbal pretraining measure compared across groups was the sequence learning task with color stimuli. Raw scores on the sequence learning tasks represented the mean length of the longest sequence correctly replicated. Performance was significantly better for the subjects with typical hearing on both the repeating and novel sequence learning tasks with color stimuli. Findings from previous studies help to explain this difference between groups. Sequences were made up of red, yellow, green, and blue circles, and although the subjects were not required to vocalize or name a color as they replicated sequences, previous studies have shown that performance can be affected by the nameable quality of stimuli (Dawson et al., 2002). In the Dawson et al. (2002) study, subjects who were deaf or hard of hearing performed similarly to subjects with typical hearing on an imitative task that did not lend itself to verbal coding but performed more poorly recalling sequences of pictures depicting a fish or a dog. Conrad (1973) also reported more errors by subjects who were deaf or hard of hearing on phonologically similar sequences indicating a lack of verbal rehearsal by this group. Bebko and McKinnon (1990) found that spontaneous rehearsal for children with typical hearing emerges two to four years earlier than for children who are deaf or hard of hearing educated in spoken language settings. It is plausible that in the current study fewer children in the deaf or hard of hearing group utilized a rehearsal strategy when presented with nameable stimuli, thus contributing to their lower performance on the color sequence learning tasks. Additionally, as described by Baddeley (1992), the phonological loop assists with the memory process as a nameable object triggers the act of rehearsal through subvocal repetition. Therefore poorer memory for stimuli that can be verbally coded may be an indication of poorer working memory ability in subjects who are deaf or hard of hearing.

Performance within each group was better on the repeating than on the novel sequencing task with color stimuli, yet the typically hearing subjects still performed significantly better than those who were deaf or hard of hearing on both tasks. As previously described, the repeating task required subjects to build a sequence by remembering previous information while receiving new input and then adding that to the temporarily stored information. The novel task presented a new sequence each time so information did not need to be held for later manipulation; instead it moved in and out of short-term memory very quickly. It is possible that the repetitive nature of the repeating task makes it conducive to verbal rehearsal as the subject rehearses the previous sequence while awaiting the addition of a new component. Here again the ability to rehearse may be one factor that helps to explain the better performance on the repetitive task as compared to the novel task. Efficient use of phonological rehearsal may have direct implications for language acquisition; by helping to retain or learn repeated stimuli, phonological rehearsal may also facilitate vocabulary learning and other aspects of language that are repeated within and across sentences. Again the poorer performance by the deaf or hard of hearing subjects may indicate general implicit learning or working memory deficits.

Table 3 displays the significant differences between the two groups on two of the three nonverbal measures as well. Each of these nonverbal tasks required memory for sequences with stimuli that were not conducive to verbal coding. As previously discussed, a period of auditory deprivation results in a degraded auditory signal and diminished access to naturally occurring sequences of sound. As proposed in other studies (Conwayet al., 2009; Saffran et al., 1996), the number of complex sequential patterns received by a child early in life may play a significant role in general sequence learning and language ability. Results from the WRAML 2 finger window task support this idea. In this nonverbal sequence task subjects were merely required to replicate a sequence by pointing a finger. The mean scaled score of 9.47 by the subjects who were deaf or hard of hearing was significantly lower than the mean of 11.41 obtained by the typically hearing group. A mean scaled score below ten represents performance in the low average range (Adams & Sheslow, 2003). It is reasonable to conclude that this deficit in sequence ability by the deaf or hard of hearing subjects results from the reduced input of auditory sequences for this group. Given the sequential nature of language, this lower performance on a sequence memory task may provide insight into the underlying factors contributing to the deficits in language development commonly exhibited by children who are deaf or hard of hearing.

Results of the computerized sequence learning tasks with nonverbal stimuli provided interesting information as well. The mean length of the longest repeating sequence with black and white stimuli was significantly different between groups. Although the black and white figures did not readily lend themselves to verbal coding, it seems likely that the repetitive nature of the repeating black and white task aided the typically hearing group in remembering sequences. Some subjects were observed counting the flashes (either saying numbers aloud or mouthing them quietly) in different locations on the grid as the sequence was repeated and lengthened. This provided evidence of verbal rehearsal as a strategy for remembering the sequence. Subjects who were deaf or hard of hearing frequently pointed as the flashes appeared but rarely was any vocalization or mouthing of words observed. Once again the failure to effectively use rehearsal strategies may have contributed to the differences in performance by the two groups.

The novel sequence learning task with black and white stimuli proved to be the most difficult task for both groups. The mean sequence length was lower on this task than for the repeated sequences with black and white stimuli for deaf or hard of hearing and typically hearing subjects alike. However, on this task there was no significant difference between groups. Furthermore, the difference in mean sequence length for the repeating and novel black and white tasks was not as great for the deaf or hard of hearing subjects as it was for the typically hearing group. For the typically hearing group the combination of nonverbal stimuli and the novel presentation seemed to remove the opportunity to use verbal rehearsal to assist with remembering a sequence. As noted above, the group that was deaf or hard of hearing did not seem to utilize any rehearsal strategy with the repeating task and as such were presumably less impacted by the novel presentation combined with the black and white stimuli.

In summary, the subjects who were deaf or hard of hearing performed more poorly on most tasks that allowed for verbal coding whether they were presented visually or auditorily. It is likely that the deaf or hard of hearing subjects are not implementing verbal rehearsal to aid in the retention of verbal information as evidenced on the nonword and computerized sequence learning tasks with color stimuli. In addition, they also performed more poorly than their typically hearing peers on the naming task of the NEPSY-II. This inability to quickly retrieve and state the name or direction of a visually represented object indicates the absence of a strong link between the visual stimuli and its verbal description for subjects who were deaf or hard of hearing and perhaps a different type of storage mechanism for verbal stimuli. The only verbal tasks that did not reveal significant differences between the two groups were the inhibition and switching tasks of the NEPSY-II. The additional cognitive load brought on by these tasks affected the performance of the typically hearing subjects. However, performance did not drastically decrease for the subjects who are deaf or hard of hearing which suggests that they are less impacted by the additional inhibitory requirement of these tasks. Differences between the two groups were also revealed on some of the nonverbal tasks. The subjects who were deaf or hard of hearing again performed more poorly on tasks of sequentially presented material with significant differences revealed on both the WRAML 2 and the computerized repeating sequence learning task with black and white stimuli. The presence of a group difference for the repeating but not for the novel sequence learning task with nonverbal stimuli suggests that the subjects who are deaf or hard of hearing were not implicitly learning serially presented information and thus were not as affected when the repetitive nature of the task was removed. Taken together these findings suggest that the impact of sensory deprivation associated with a hearing loss extends beyond the reception of an auditory signal to other more general cognitive abilities. Specifically it appears that the subjects who are deaf or hard of hearing experience difficulty with temporally presented sequential information and do not utilize verbal rehearsal strategies to assist them.

Correlations of assessment measures with the PPVT 4, as shown in Table 4, revealed a significant correlation for the group with typical hearing on only one assessment measure, the repeating sequence learning task with color stimuli. The presence of a significant relationship between a measure of language ability and performance on a sequencing task with nameable stimuli for the group with typical hearing but not for the group who were deaf or hard of hearing provides additional support of the findings by Bebko & McKinnon (1990). That study proposed that language experience was a significant mediating variable in the relationship between age and the use of rehearsal strategies. Mastery of language, then, was likely a necessary prerequisite for the utilization of a linguistically based strategy such as rehearsal. In the current study, language ability was measured by scores on the PPVT 4 and as seen in Table 4 was not found to be highly correlated with the verbal repeating sequence learning task with color stimuli for subjects who were deaf or hard of hearing. Bebko &

McKinnon (1990) maintain that if children have not achieved a level of automaticity with their language skills they will not be able to successfully implement a rehearsal strategy. Results from the NEPSY-II naming task showed this level of automaticity to be lacking for the deaf or hard of hearing subjects. This finding, combined with the lack of a significant correlation between PPVT 4 and the repeating color sequence learning tasks, supports the theory that subjects who are deaf or hard of hearing are not utilizing rehearsal strategies when attempting to remember a sequence of nameable objects.

A number of tasks were significantly correlated with scores from the PPVT 4 for the deaf or hard of hearing group as shown in Tables 4 and 5. Correlations were significant on both the naming and inhibition tasks of the NEPSY-II inhibition subtest. In addition, number of nonwords correctly produced was positively and significantly correlated while the number of syllable errors was negatively and significantly correlated with the PPVT 4. These significant correlations between the PPVT and other verbal measures for the deaf or hard of hearing group suggest a relationship between language development (as measured by receptive vocabulary scores) and other verbal tasks requiring cognitive and memory ability.

There was also a significant correlation between the PPVT 4 and the nonverbal WRAML 2 finger window task for this group. This result again provides support for the idea that a period of auditory deprivation may have an impact beyond hearing acuity to sequence abilities in general. In addition it supports the theory proposed by Conway et al. (2010) who provided empirical evidence of a significant correlation between improvement of immediate serial recall of statistically structured sequences and performance on a word predictability task. Based upon findings in this study the authors concluded that the development of language skills appears to be facilitated by greater sensitivity to the underlying structure of sequential patterns.

Table 6 shows correlations between measures for each group as well as significant differences between the two groups for these correlations. As shown in this table, significant differences between correlations of measures for the deaf or hard of hearing group and the typically hearing groups were revealed on a number of the computerized sequence learning tasks. Specifically, correlations were significantly different for the two groups for the correlations between the novel sequence task with color stimuli and three other sequence learning tasks (the repeating with color, the repeating with black and white, and the novel with black and white stimuli). A significant correlation was revealed between verbal and nonverbal sequence tasks for the deaf or hard of hearing group. This indicates a failure to exhibit the predicted advantage for remembering nameable stimuli and adds further merit to the theory that the deaf or hard of hearing subjects did not utilize a verbal rehearsal strategy to assist in the task of sequence learning.

There was another significant difference between groups on the correlation between the repeating black and white and the novel black and white sequence tasks. The deaf or hard of hearing subjects performed similarly on both tasks which presented non-nameable stimuli while the typically hearing subjects gained some advantage from the repeating nature of the task. Again it may be presumed that some type of rehearsal strategy was employed by the subjects with typical hearing. The overall differences in performance on the sequence learning tasks suggest a broad deficiency in sequence learning ability among the subjects who were deaf or hard of hearing, a finding which supports previous research showing that these subjects experience difficulty performing sequencing tasks (Conway et al., in press; Furth & Pufall, 1966).

Analyses of performance on the visuospatial sequencing task did not reveal any significant improvements over time for either group or in either condition, yet the difference between groups provided some interesting information. The subjects who were deaf or hard of hearing performed significantly more poorly than the typically hearing subjects in both the adaptive and control conditions of the visuspatial sequencing task. When examined more closely, performance by each group in each condition provides additional information. The percent of correct responses for each day of visuospatial sequencing practice was calculated and revealed that subjects who were deaf or hard of hearing performed at a level between 45% and 49% correct in both the adaptive and control conditions indicating a general deficit in sequencing skills. For typically hearing subjects the percentage correct was quite different for the adaptive and control conditions. Average percent correct ranged from 49% to 52% in the adaptive condition, while in the control condition this percent ranged from 72% to 79%. The adaptive version of the task was designed to adjust and match the individual memory span of the subjects and accuracy scores around the 50% range for both groups in the adaptive condition suggest that this was the case. The percentage correct for the deaf or hard of hearing subjects in the control condition was also in that range, however. This finding makes it plausible to conclude that the sequence length of three which was intended to be below the capacity limit of the subjects was actually closely matched to the ability level of the deaf or hard of hearing subjects in the control condition.

Figure 6 displays visuospatial sequencing data for the average number of correct taps made per set for each session for subjects in the control condition.   As previously explained, a maximum daily average of 90 correct taps per set could be obtained in the control condition. The group with typical hearing achieved a high level of accuracy. Scores for the subjects who were deaf or hard of hearing were 25 to 30 points lower and suggest possible difficulty in performing the task. This poorer performance is consistent with the data from the percent correct previously sited and supports the suggestion that a constant sequence length of three actually challenged the deaf or hard of hearing subjects in the control condition. As a result deaf or hard of hearing subjects in the condition that was intended to serve as a control may inadvertently have been provided the same benefit as subjects in the adaptive condition.

The failure for subjects to improve on the visuospatial sequencing task over time may call into question whether improvements on untrained measures may actually be attributed to any training effect at all. While this is certainly a valid point, some have argued that the effort put forth on a training task may enhance attentional focus thereby stimulating a set of strategies which can be utilized across a variety of tasks (Holmes et al., 2009). Given that the deaf or hard of hearing subjects in the control condition appeared to be just as challenged by the task as both groups in the adaptive condition, it is possible that all three of these groups would show some effect from the attention and concentration associated with the task.

In summary, the findings related to group differences on pretraining assessments support the first hypothesis of this study that a difference by hearing status would be revealed on a variety of verbal and nonverbal tasks.   Correlations between some verbal and noverbal tasks were revealed for the subjects who were deaf or hard of hearing. In addition, performance over time on the visuospatial sequence task by subjects who were deaf or hard of hearing was significantly poorer than that of typically hearing subjects in the control condition. These findings provide evidence of an overall deficit in sequence memory for subjects who are deaf or hard of hearing as well as a diminished use of phonological verbal rehearsal. These data are consistent with results from previous studies showing poor working memory ability and suggesting that a period of auditory deprivation may alter the path for typical development of speech, language, and other sequentially based abilities. Researchers agree that sequence learning is an underlying skill necessary for successful spoken language development (Conway & Pisoni, 2008; Furth & Pufall, 1966). It is plausible that deficits in sequence memory may have cascading effects on speech, language, and reading ability and may help to explain the delays exhibited in these areas by children who are deaf or hard of hearing. It is important then that interventions and habilitation with these children reflect these findings by targeting sequencing and phonological memory skills as a possible means of improving language outcomes for children who are deaf or hard of hearing.

Effects of Visuospatial Sequence Training

The second major aim of this study was to determine if visuospatial sequence practice would result in improvements to nontrained tasks measuring working memory and executive function. Discovering methods which bring about improvement on a verbal short-term memory task (the nonword repetition task) is of great importance in the area of research related to children who are deaf or hard of hearing because it brings with it the promise of improving language abilities as well. The second major hypothesis of this study proposed that visuospatial sequencing practice would lead to improved performance on a variety of cognitive tasks.

As earlier reported, nonword repetition performance was examined in a 2 (Hearing Status) x 2 (Training Condition) x 3 (Time) repeated measures ANOVA with the last factor treated as repeated measure with unequal spacing. The findings from these analyses suggest that significant benefits may be derived from visuospatial sequencing practice. Analyses were performed for the total number of syllable errors produced by each group and in each condition as well as the number of syllable errors for nonwords at each syllable length. A Time x Training Condition effect was revealed both for total syllable errors as well as syllable errors of 4 syllable nonwords. Figure 10 shows the mean total syllable errors made across testing sessions for the adaptive and control groups. It is evident that total syllable errors were reduced in the adaptive condition for both typically hearing and deaf or hard of hearing subjects, indicating that adaptive sequences led to improvement in the ability to match the number of syllables that were presented in a target word. Figure 11 shows the syllable errors made by each group in each condition. Although the decrease in syllable errors did not reach significance for any single group in a particular condition, an obvious trend for improvement was seen for the deaf or hard of hearing subjects in the adaptive condition. It is plausible that a larger sample and/or a longer training period might have revealed a significant effect.

A similar effect was revealed for syllable errors of 4 syllable nonwords. As shown in Figure 12, subjects in the adaptive condition in both groups improved significantly from pretraining to the second posttest. Figure 13 separates these results by group and condition. Once again a trend for improvement is evident for the deaf or hard of hearing subjects in the adaptive condition. Here again the lack of a significant effect for hearing status for these subjects may have been due to the small number of subjects in that group or the relatively short training period. With the addition of more subjects and/or more visuospatial sequencing sessions it is possible that the deaf or hard of hearing subjects in the adaptive condition would have shown a significant improvement over time.

Analyses were also performed for the number of nonwords produced correctly. Results from the analysis of total number of correct nonwords revealed a significant effect for time with all subjects in both conditions improving over the three testing sessions as displayed in Figure 8. No interactions for hearing status or training condition emerged. One possible explanation for an overall improvement is that the visuospatial sequencing regimen was not long enough to produce an effect by condition. Another possible explanation emerges when performance is looked at a bit differently. Although there was no significant interaction by group or condition, an interesting trend was discovered by differentially examining the mean number of correctly produced nonwords for the deaf or hard of hearing group and the typically hearing group. The light and dark shading in Figure 8 reflects the portion of total correct words contributed by each group. Subjects who were deaf or hard of hearing correctly produced 21% of the total correct words at the pretraining session. By the first posttest this percent was 23%, and at the second posttest the deaf or hard of hearing subjects produced 24% of the total correctly produced words. The increase by the subjects who were deaf or hard of hearing regardless of condition supports the earlier suggestion that some benefit from performing the visuospatial sequencing task may have been received by the deaf or hard of hearing group in the control condition. Improvement was not as great for the typically hearing subjects as for the deaf or hard of hearing subjects but they also showed improvement over time. This result also suggests that typically hearing subjects in both the adaptive and control conditions received some benefit from replicating visuospatial sequences. Although further research is required in order to determine the merit of this explanation, the main effect for time that was revealed for correct production of nonwords is nonetheless an important finding. If subjects show improvement of nonword production just by repeatedly performing this task, then consideration should be given to implementing tasks of nonsense word imitation into classroom instruction. Previous studies have shown that nonword repetition is linked to vocabulary and other language skills. Therefore improvement on this task may potentially carry over to improvement in these areas for typically hearing and deaf or hard of hearing children alike.

Additional analyses performed for correct nonword production at each syllable length revealed similar effects for time for nonwords that were 2, 3, and 4 syllables in length. However, a significant Hearing Status x Training Condition x Time interaction emerged for the number of correctly produced 4 syllable nonwords. Figure 9 shows the performance for each group in each condition at the three testing sessions. No improvement was shown for the typically hearing subjects in the control condition. Based upon the ease with which the typically hearing control group completed the sequencing task and their lack of improvement on the nonword task it appears that they received no benefit from visuospatial sequencing practice that would transfer to a phonological memory task. As Figure 9 also shows, the typically hearing group in the adaptive condition as well as the subjects who were deaf or hard of hearing in both the adaptive and control conditions showed a trend for improvement across the testing sessions. Although these increases for deaf or hard of hearing subjects did not reach significance in either the adaptive and control conditions, they indicate a trend for improvement in general verbal sequence memory ability following visuospatial sequencing practice. This increase of correctly produced nonwords in both conditions lends further support to the notion that the sequences presented in the control condition provided benefit for the subjects who were deaf or hard of hearing. It is plausible then that with a different control and a larger sample size, results would show that adaptive presentation of visual sequences transfers to improvement on a verbal task of phonological memory.

The implications from these improvements on tasks of phonological memory following visuospatial sequencing practice are promising. As previously noted, producing a nonword response utilizes the same underlying linguistic processes as recognizing and repeating real words. Earlier findings revealed that scores on the PPVT 4 were correlated with nonword performance for the deaf or hard of hearing subjects. In addition, the nonword task has also been shown to be correlated with syntax abilities (Carter et al., 2002). As such it is plausible to predict that remembering and correctly repeating a nonword may ultimately lead to improved ability on other verbal tasks including receptive and expressive vocabulary and syntax development. Moreover the results indicate that visuospatial sequencing practice also provides a benefit to typically hearing children which presents implications for application to the general education setting as well.

Results from analyses of other assessment measures also warrant discussion. Analyses performed on the repeating sequence learning task with color stimuli revealed a significant Hearing Status x Time x Training Condition interaction. Figure 14 shows that the typically hearing control group made significant improvement from pretraining to the first posttest as well as from pretraining to the second posttest. The reason for this improvement and a simultaneous decline in performance by the typically hearing adaptive group does not seem clear. One possible explanation might be that the adaptive presentation of the sequences taxed the sequencing abilities that these subjects needed to use in replicating the repeating and novel sequence learning tasks, resulting in an opposite effect of the one desired. Conversely, replication of the visuospatial sequences by the typically hearing subjects in the control condition indicated ease in performing the task which may have facilitated transfer to the repeating and novel sequencing task with color stimuli. It is also possible that the typically hearing subjects in the control condition utilized some type of rehearsal strategy for remembering the sequences of three over the 10 sessions and that they effectively carried that strategy over to the task of remembering repeated sequences of colored stimuli. Of interest on the repeating sequence learning task with color stimuli was the finding that although subjects in the deaf or hard of hearing group who received the adaptive sequences performed significantly more poorly than those in the typically hearing adaptive group at pretraining that difference did not remain significant at either posttest.

The typically hearing control group again showed more improvement on the novel sequence learning task with color stimuli than their peers in the adaptive group as displayed in Figure 15. It is again unclear why the typically hearing adaptive group did not make gains over time. The subjects who were deaf or hard of hearing in the adaptive condition, however, did make steady though not significant progress over time. This tendency toward an increase in sequence length for subjects in the adaptive condition suggests the possible transfer from a nonverbal sequencing task to one with stimuli that can be verbally coded. The lack of a significant difference in performance between the adaptive and control conditions for the subjects who were deaf or hard of hearing might once again be due to a the challenge faced by the subjects in the control condition. It is possible that an increase in the number of visuospatial sequencing sessions combined with a shortened sequence length in the control condition would lead to distinguishable differences between the conditions.

Results for the NEPSY-II inhibition task as well as the combined naming versus inhibition task revealed a significant effect for time, a finding which is consistent with improvement over time that emerged for production of nonwords. Mean scaled scores for all NEPSY-II tasks at all three testing sessions are located in the descriptive statistics tables in Appendix D. On the inhibition task, scores for all subjects registered below the mean score of ten at pretraining but were at or above the mean at the first posttest and continued to improve at the second posttest. As noted earlier, low performance on the inhibition task indicates impulsivity or slow processing speed resulting from the inhibitory demands of the task. Improvement on the inhibition task may have been a consequence of experience with the sequencing task because subjects became accustomed to waiting for an entire sequence to be presented before tapping a response. Additionally, the deaf or hard of hearing subjects in the control condition again might have experienced a benefit despite the fixed nature of the sequences presented to them. It is also possible that there was no effect for training but that repeated performance of the inhibition task led to improvement. Even if improved performance was due to a practice effect, the benefit should not be overlooked. Better performance on the inhibition task may indicate improvement in impulsivity control, and attention and inhibition are executive functions which contribute to academic success (Shalev et al., 2007). Therefore improvement on the NEPSY-II subtest suggests that the benefits of visuospatial sequence practice may transfer to academic performance as well.

The switching condition of the NEPSY-II showed an effect for time as well. The means for this assessment measure across sessions can be found in Appendix D.1 through D.3. This task, with the added challenge of changing a response based upon features of the stimuli, is designed to identify problems with cognitive flexibility. Improvement was made by all subjects on this task across the three testing sessions. For the inhibition versus switching task, however, a Time x Hearing Status effect emerged. Performance by the typically hearing group significantly improved over time, but the deaf or hard of hearing group did not show similar gains. This result may indicate that the cognitive load associated with this task was too great for the subjects who were deaf or hard of hearing despite the gains shown in other conditions of this subtest.

The WRAML 2 was the only nonverbal measure that revealed any significant results, with all subjects in both conditions showing improvement across the posttraining sessions. There was a significant effect for hearing status and for time on the finger window subtest, but no interaction emerged. A Time x Hearing Status effect, did however approach significance, $F(2,112) = 3.04$, $p = .052$. Mean scaled scores for this measure are presented in Appendix D and show an increase for the deaf or hard of hearing group from 9.3 at pretraining to 10.4 at the first posttest and a leveling off to 9.7 at the second posttest. Test-retest information provided in the WRAML 2 Administration and Technical Manual (Sheslow & Adams, 2003) lists an expected gain of 0.2 on the finger windows subtest. Considering that the improvements over time achieved by subjects in this study far exceeded those predicted by the test-retest reliability and that the control condition might have provided benefit for the deaf or hard of hearing subjects, it is plausible to conclude that the visuospatial sequencing regimen led to improvement on this nontrained visuospatial task.

In summary, the findings related to effects of visuospatial sequencing practice revealed improvement on a task of verbal memory. Specifically, the findings provide strong support that the adaptive sequences improved phonological memory as evidenced by the performance on the nonword repetition task. The number of syllable errors decreased for subjects with typical hearing and those who were deaf or hard of hearing in the adaptive condition. The number of correctly produced nonwords increased for all subjects which may be a consequence of inadvertent benefits of practice for the deaf or hard of hearing subjects in the control condition. Given the relationship between nonword repetition and a variety of language abilities, these results provide promise for improving other language related abilities such as vocabulary, syntax, and reading through the implementation of a visuospatial sequencing program.

In addition, practice replicating visuospatial sequences resulted in general improvement for combined groups and conditions on a number of tasks. This may be an indication that practice on these tasks will bring about improvement, though the level of improvement displayed by subjects on the NEPSY-II and the WRAML 2 exceeded the test-retest improvements projected in the test manuals. It is also plausible that the control condition provided some actual benefit for the subjects who were deaf or hard of hearing.

Considering the interconnectedness of cognitive abilities and the role they play in language development, improvement of phonological memory and the executive function of inhibition which were revealed in this study provide promise for improved language and reading outcomes for children who are deaf or hard of hearing following visuospatial sequencing practice.

Study Limitations

There were several limitations to the study that should be addressed. First, the number of children in the study was relatively small. This is due in large part to the difficulty in obtaining subjects for the deaf or hard of hearing group. Recruitment was limited to two private schools in a finite geographic area. Larger numbers of children might be obtained by recruiting from public schools as well. The fact that no monetary reward was given for participation, however, made the prospect of recruiting from that population less likely. In addition, deaf or hard of hearing subjects who participated in this study were all enrolled in educational programs emphasizing listening and spoken language skills. It would be of interest to include children with sign language skills to determine any similarities with the group in the current study in pretraining characteristics as well as performance on the visuospatial sequencing task and post training results.

There were some limitations associated with the typically hearing group as well. Average performance on the PPVT 4 by the group of children with typical hearing was nearly one standard deviation above the mean. Since no other tests of language or intelligence were administered it is not known if their skill level was above average on other tasks as well. Additionally, while scaled scores allowed for comparison with normal distributions on some tasks, only raw scores were available for a few of the measures. It would be useful to have a larger and more diverse sample of typically hearing children in order to obtain more representative baseline measures for these tasks.

Next some aspects of the assessment measures deserve consideration. Some students displayed a lack of interest in performing multiple sequence learning tasks during the assessment sessions. Thought should be given to breaking one session into several smaller sessions or providing a longer break and possibly a snack between tasks. Additionally, all tasks of the NEPSY-II subtest could not be administered to children under the age of seven so an alternate test of inhibition might be considered. Consideration should also be given to including additional language measures, both as part of the baseline and as tasks to measure effects of visuospatial sequencing practice. The PPVT 4 gives receptive vocabulary scores, but it does not provide information about overall language performance. Likewise the Children's Test of Nonword Repetition does not provide information about a child's ability to produce connected speech.

Several issues related to the design of the visuospatial sequencing task should be addressed as well. As mentioned earlier, the task of replicating sequences that were three in length appeared to be difficult for subjects who were deaf or hard of hearing in the control condition. Future implementation of this visuospatial sequencing task should consider shortening the standard sequence length of three so that the task clearly does not present a challenge to the subjects. If it were evident that none of the subjects in the control condition struggled with the task, then differences between the control and adaptive groups following practice might be more clearly revealed and interpreted. The number of sessions might also be increased in an effort to produce more robust results. There was a tendency for improvement by the deaf subjects in the adaptive condition which may have reached significance with a larger sample size, a clearer distinction between adaptive and control conditions, and a longer practice period.

An additional issue arose with regard to interest level for the task. A number of subjects expressed a disinterest in continuing the task at some point during the practice sessions. The only feedback provided to the subjects was a number which appeared on the touch screen monitor indicating the number of correct taps made by the subject at the end of each set of 30 sequences. This did not provide adequate reinforcement, and as a result motivation to perform the task waned over the course of the ten sessions for some subjects in each group and in both the adaptive and control conditions. The visuospatial sequencing task might be redesigned so that performance was acknowledged and "rewarded" with exciting and motivating graphics.

Future Research and Implications

The findings from this study provide an encouraging first step in the attempt to identify and address differences between children who are deaf or hard of hearing and those with typical hearing with the goal of improving sequence memory and language abilities. Future research should include additional assessments of language performance as baseline measures. The Clinical Evaluation of Language Fundamentals (CELF) is an accepted measure of language performance covering a wide range of skills. Since the CELF is typically administered as part of an annual battery to many children who are deaf or hard of hearing, scores from this would likely be readily available to researchers.

An additional verbal task that includes elements of language beyond those measured with the nonword test should also be added to the assessment sessions. Additionally, future studies should consider refining the choice of assessment measures so that they are appropriate for the age levels of all participants.

In order to make a clear distinction between the effects of adaptive and control conditions, further research should implement a control condition with a sequence length at a level truly below the limit capacity of the subjects. An additional option would be to include a third condition in which subjects would not take part in any sequencing practice. This might then provide a truer control as well as a means for determining a mere practice effect on the pre and post training assessments. The duration of the visuospatial sequencing practice should also be considered. If the task could be made more engaging, number of days might be extended beyond the current ten of this study. A greater number of sessions may result in clearer differences and perhaps greater effects between the control and adaptive conditions. Future studies should also be designed to track progress over time. In a longitudinal study specific aspects of language and reading development more relevant to the educational setting could be addressed. In addition, a neuroimaging component could be incorporated into this study to provide additional information regarding the reorganization of neural networks and to provide physical evidence in conjunction with behavioral findings. Finally, some means of determining and then classifying subjects based upon their use of phonological rehearsal strategies might provide additional information as well. In addition to being observed, subjects could be surveyed following the sequencing tasks to determine any strategies that they employed to help them remember. This information may shed further light on the similarities and differences between groups that lead to successful task completion.

Based upon the initial findings of this study some long-term applications might be considered as well. First of all it seems clear that some benefit was gained from visuospatial sequencing practice. Although additional research is required to verify these results and to determine any long term effects, it seems plausible that educational practices which rely solely on auditory input may be missing out on an opportunity to provide practice with temporal sequential stimuli, an essential component of language-learning. As further research unfolds, more light may be shed on the nature of the relationship between sequence memory and language development thereby providing insight into the factors which contribute to the wide variability among cochlear implant recipients. As such, consideration should be given to developing a battery of assessments that can be used for counseling parents considering cochlear implants for their child. If poor sequence abilities do in fact affect language development then parents should have information regarding their child's level of ability as well as suggested strategies for bringing about improvement in this area. Such a battery could also be used as a type of screening to identify children with low sequence learning abilities. These results in conjunction with information gained from more conventional assessments such as Digit span may help to identify children who are "at risk" for slower language development.

Perhaps most importantly future studies should focus on a means of transferring research findings into practical application. Information about the cascading effect of hearing loss on other cognitive skills as well as potential means of improving these skills needs to reach educators of the deaf. If language outcomes can be improved from this type of intervention there is potential to impact the approaches taken for habilitation. Future studies might then consider modifying the visuospatial sequencing task to a portable size so that it can be implemented with children of all ages in classroom settings. Visuospatial sequencing practice may eventually be adapted to become a part of early intervention curriculum in an effort to offset some of the sequencing deficits which appear to result from a period of auditory deprivation.

The importance of this current study truly lies in the potential to impact the future study and education of children who are deaf or hard of hearing. Moving forward it is imperative that research findings make their way into educational settings if we truly expect to change language and reading outcomes for children who are deaf or hard of hearing. This clearly demands that research aimed at improving auditory capabilities must be informed by research from cognitive fields and ultimately integrated into classroom settings. As summed up by Detterman and Thompson (1997) in a report on special education, a thorough "understanding of cognitive abilities must then be used to fashion rational plans for educational intervention" (p. 1089). It is only through a sharing of information among these groups that we can hope to finally improve language outcomes for children who are deaf or hard of hearing.

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Appendix A. Parent Questionnaire

09-118

Subject number _________

Please complete the following questionnaire, place it in the envelope marked "parent questionnaire," and mail it to me at the address provided.

All the data obtained below will be kept confidential by using a coded system. Your child's personal information will only be listed on a hardcopy master list that will be kept in a locked file cabinet in Michelle Gremp's locked office.

Your gender: M F Your date of birth_____________________

Study participant's gender: M F Study participant's date of birth__________

How many siblings does the study participant have? ________
List gender and date of birth for each:

Age at which hearing loss was identified:_________

Cause of hearing loss, if known: _________________

Degree of hearing loss: ___moderate ____ severe ____ profound

Age of initial amplification: Right ear:___________ Left ear:________

Date of implantation (if applicable): Right ear: ____________ Left ear: __________
If child has cochlear implant, please indicate the following if known:
speech coding strategy _________
number of active electrodes ___________
type of CI processor ________________

Did your child receive early intervention service? ______ no ______ yes.

If yes, please indicate where and for how long.___________________________

____

Has your child been diagnosed with ADHD? _______no ________yes

Please list any additional diagnoses: ____

WU
HRPO
Approved 10/19/09

Gremp
Parent questionnaire, 1

Subject number ________

For the remaining questions, please answer in regards to the study participant's primary caregiver. If you are the primary caregiver, then answer these questions in regards to yourself. If you are not the primary caregiver, please answer to the best of your knowledge. If you are unable to answer any of the questions, please write UNSURE.

1. Please circle *primary caregiver's* ethnicity (optional):

a. Hispanic or Latino
b. Not Hispanic or Latino
c. Do not wish to report

2. Please circle *primary caregiver's* race (optional):

a. American Indian or Alaskan Native
b. Asian
c. Native Hawaiian or Other Pacific Islander
Black or African American
White
More than one race
Other
Do not wish to report

3. What is the *primary caregiver's* first language(s) spoken:______________________

4. Is the *primary caregiver* a fluent speaker of a foreign language? Yes No

If "YES," which language?______________________________

5. Please circle the highest level of education the *primary caregiver* has completed:

a. Did not graduate high school
b. High school
c. Some college, please indicate number of semesters completed:_______
d. Associate's Degree
e. Bachelor's Degree
f. Master's Degree
g. PhD

6. Is the *primary caregiver* currently:

a. Unemployed
b. Student – unemployed
c. Employed, part-time

Gremp
Parent questionnaire, 2

d. Employed, full-time
e. Keeping house
f. Retired

7. Is the *primary caregiver* currently:

a. Married
b. Widowed
c. Divorced
d. Employed, full-time
e. Separated
f. Never Married

8. Is the *primary caregiver's spouse/partner*:

a. Unemployed
b. Student – unemployed
c. Employed, part-time
d. Employed, full-time
e. Keeping house
f. Retired
g. N/A

9. Which category best describes the *primary caregiver's* combined yearly household income?

a. Less than $15,000
b. $15,001 to $20,000
c. $20,001 to $25,000
d. $25,001 to $30,000
e. $30,001 to $40,000
f. $40,001 to $50,000
g. $50,001 to $60,000
h. $60,001 to $70,000
i. $70,001 to $80,000
j. $80,001 to $90,000
k. $90,001 to $100,000
l. $100,001 to $150,000
m. Greater than $150,001

APPENDIX B. Subject Characteristics for Deaf or Hard of Hearing Group

Subject	Degree of hearing loss		Device type			
	Right ear	Left ear	Right ear	Left ear	Early intervention	ADHD
S1	Profound	Profound	CI	CI	Yes	No
S2	Profound	Moderate-profound	HA	CI	Not reported	No
S3	Profound	Profound	CI	CI	No	No
S4	Moderate-severe	Moderate-severe	HA	HA	Not reported	Yes
S5	Mild-severe	Mild-severe	HA	HA	Not reported	Yes
S6	Severe-profound	Severe-profound	CI	HA	No	No
S7	Moderate-profound	Within normal limits-profound	CI	HA	Yes	Yes
S8	Mild-moderate	Mild-moderate	HA	HA	No	No
S9	Severe	Severe	CI	HA	No	No
S10	Profound	Profound	CI	CI	Not reported	No
S11	Profound	Profound	CI	CI	Yes	No
S12	Profound	Profound	CI	CI	Yes	No
S13	Severe-profound	Severe-profound	CI	CI	Yes	Yes
S14	Moderate	Moderate	HA	HA	Yes	No
S15	Severe	Severe	HA	CI	Yes	No
S16	Profound	Profound	CI	CI	Yes	No

S17	Severe-profound	Severe-profound	HA	CI	No	No
S18	Moderate	Moderate	HA	HA	No	No
S19	Severe-profound	Severe-profound	HA	CI	Yes	No
S20	Profound	Profound	CI	CI	Yes	No
S21	Mild-moderate	Mild-moderate	HA	HA	Not reported	No
S22	Mild-moderate	Mild-moderate	HA	HA	Not reported	No
S23	Profound	Profound	CI	CI	Not reported	No
S24	Profound	Profound	CI	CI	Yes	No
S25	Moderate-profound	Moderate-profound	CI	HA	Yes	Yes
S26	Profound	Profound	CI	HA	Yes	Yes
S27	Severe-profound	Severe-profound	CI	CI	Yes	No
S28	Moderate	Moderate	HA	CI	No	No
S29	Moderate	Moderate	CI	HA	Yes	No
S30	Profound	Profound	HA	HA	Yes	No
S31	Profound	Profound	HA	HA	Yes	No
S32	Profound	profound	HA	HA	No	No

APPENDIX C. Words for Nonword Repetition Assessment

Number of syllables	Target nonword	Target nonword IPA transcription
2	Ballop	ˈbæ.ləp
	Prindle	ˈpɹin.dl
	Rubid	ˈɹuˌbid
	Sladding	ˈslæ.diŋ
	Tafflist	ˈtæ.flist
3	Bannifer	ˈbæ.nəˌfɚ
	Berrizen	ˈbɛ.ɹəˌzin
	Doppolate	ˈdɑ.pəˌleit
	Glistering	ˈgli.stɚ.iŋ
	Skiticult	ˈski.ɾəˌkʌlt
4	Comisitate	kəˈmi.səˌteit
	Contramponist	kənˈtɹæm.pəˌnist
	Emplifervent	ɛmˈpli.fɚˌvɛnt
	Fennerizer	ˈfɛ.nɚˌai.zɚ
	Penneriful	pəˈnɛ.ɹəˌfʌl
5	Altupatory	ælˈtu.pəˌtɔ.ɹi
	Detratapillic	diˈtɹæ.ɾəˌpi.lik
	Pristeractional	ˈpɹi.stɚˌæk.ʃə.nl
	Versatrationist	ˈvɚ.səˌtɹei.ʃəˌnist
	Voltularity	ˈvɑl.tʃʊˌlɛ.ɹəˌti

APPENDIX D.1. Pretraining Descriptive Statistics by Hearing Status

	Deaf or hard of hearing			Typical hearing		
	N	Mean	SD	N	Mean	SD
Age at start of training in months	32	94.69	21.44	29	93.21	11.38
PPVT 4 standard score	32	79.34	15.61	29	115.21	12.53
PPVT 4 raw score	32	86.88	24.67	29	144.34	22.51
Verbal tasks						
NEPSY-II						
Naming scaled	30	8.83	3.55	21	11.33	2.67
Inhibition scaled	28	8.14	3.14	21	9.76	2.97
Switching scaled	16	7.88	2.53	11	9.09	2.59
Naming vs inhibition scaled	28	8.32	3.24	21	8.90	3.00
Inhibtion vs. switching scaled	16	7.62	1.63	11	8.18	1.72
Nonword Repetition						
Total number of words correct	32	3.09	2.52	28	13.18	3.32
2 syllable words correct	32	0.75	0.80	28	3.79	0.83
3 syllable words correct	32	1.12	0.94	28	4.07	1.12
4 syllable words correct	32	0.47	0.76	28	3.14	0.85
5 syllable words correct	32	0.66	.79	28	2.43	1.50
Total syllable errors	32	4.47	4.28	28	0.79	1.23
Syllable errors in 2 syllable words	32	0.47	0.62	28	0.07	0.26
Syllable errors in 3 syllable words	32	0.87	1.24	28	0.07	0.26
Syllable errors in 4 syllable words	32	1.22	1.50	28	0.25	0.52
Syllable errors in 5 syllable words	32	1.91	1.94	28	0.39	0.74

Sequence Learning Task						
Repeating with color stimuli	32	5.50	2.42	29	7.90	2.50
Novel with color stimuli	20	3.90	1.48	21	5.05	1.02
Nonverbal tasks						
WRAML scaled	32	9.47	2.92	29	11.41	1.99
Sequence Learning Task						
Repeating with black and white stimuli	32	5.44	2.98	29	7.55	3.21
Novel with black and white stimuli	17	4.12	1.45	19	4.68	0.89

APPENDIX D.2. Posttest 1 Descriptive Statistics by Hearing Status

	Deaf or hard of hearing			Typical hearing		
	N	Mean	SD	N	Mean	SD
NEPSY-II						
Naming scaled	30	10.00	3.77	29	11.83	3.32
Inhibition scaled	29	10.14	3.40	29	11.59	2.97
Switching scaled	17	10.24	3.21	19	12.26	2.40
Naming vs. inhibition scaled	29	10.10	3.00	29	11.00	3.06
Inhibition vs. switching scaled	18	8.33	2.03	19	13.00	2.29
Nonword Repetition						
Total number of words correct	32	3.88	3.05	28	14.54	2.52
2 syllable words correct	32	1.13	0.87	28	4.04	1.14
3 syllable words correct	32	1.50	1.30	28	4.36	0.78
4 syllable words correct	32	0.69	0.93	28	3.43	0.96
5 syllable words correct	32	0.59	0.80	28	2.75	1.43
Total syllable errors	32	3.94	4.63	28	0.43	0.69
Syllable errors in 2 syllable words	32	0.25	0.51	28	0.07	0.26
Syllable errors in 3 syllable words	32	0.56	1.13	28	0.07	0.26
Syllable errors in 4 syllable words	32	1.28	1.67	28	0.11	0.32
Syllable errors in 5 syllable words	32	1.84	1.92	28	0.18	0.48
Sequence Learning Task						
Repeating with color stimuli	32	5.31	2.57	29	8.07	3.49
Novel with color stimuli	20	3.75	1.21	21	4.901	1.00

Nonverbal tasks						
WRAML scaled	32	10.53	2.50	29	11.72	1.98
Sequence Learning Task						
Repeating with black and stimuli	32	5.31	2.60	29	8.59	3.84
Novel with black and white stimuli	17	3.65	0.93	20	4.40	1.00

APPENDIX D. 3 Posttest 2 Descriptive Statistics by Hearing Status.

	Deaf or hard of hearing			Typical hearing		
	N	Mean	SD	N	Mean	SD
NEPSY-II						
Naming scaled	29	9.76	3.83	29	12.90	3.22
Inhibition scaled	29	10.62	3.59	29	12.55	3.03
Switching scaled	15	9.53	2.90	19	13.42	2.85
Naming vs. inhibition scaled	29	10.86	2.90	29	11.76	3.15
Inhibition vs. switching scaled	14	8.71	2.02	19	12.63	3.30
Nonword Repetition						
Total number of words correct	31	4.13	3.00	28	14.29	2.88
2 syllable words correct	31	1.06	0.96	28	4.07	0.81
3 syllable words correct	31	1.55	1.31	28	4.29	0.76
4 syllable words correct	31	0.84	1.00	28	3.25	1.27
5 syllable words correct	31	0.68	0.79	28	2.68	1.25
Total syllable errors	31	3.65	4.02	28	0.25	0.65
Syllable errors in 2 syllable words	31	0.32	0.54	28	0.00	0.00
Syllable errors in 3 syllable words	31	0.58	1.06	28	0.14	0.36
Syllable errors in 4 syllable words	31	1.06	1.59	28	0.04	0.19
Syllable errors in 5 syllable words	31	1.68	1.68	28	0.07	0.26
Sequence Learning Task						
Repeating with color stimuli	31	5.71	2.74	29	8.72	3.70
Novel with color stimuli	20	4.10	0.85	21	4.95	0.97

Nonverbal tasks						
WRAML scaled	31	9.71	0.34	29	12.34	1.68
Sequence Learning Task						
Repeating with black and white stimuli	31	5.52	2.58	29	8.17	3.74
Novel with black and white stimuli	17	3.82	1.13	20	4.65	1.18

APPENDIX D.4 Device Type and Training Condition for Deaf or Hard of Hearing Subjects

Subject	Device type		Condition
	Right ear	Left ear	
S1	CI	CI	Adaptive
S2	HA	CI	Control
S3	CI	CI	Adaptive
S4	HA	HA	Adaptive
S5	HA	HA	Control
S6	CI	HA	Control
S7	CI	HA	Adaptive
S8	HA	HA	Control
S9	CI	HA	Control
S10	CI	CI	Adaptive
S11	CI	CI	Control
S12	CI	CI	Control
S13	CI	CI	Control
S14	HA	HA	Adaptive
S15	HA	CI	Control
S16	CI	CI	Adaptive
S17	HA	CI	Control
S18	HA	HA	Adaptive
S19	HA	CI	Adaptive
S20	CI	CI	Control
S21	HA	HA	Control
S22	HA	HA	Adaptive
S23	CI	CI	Adaptive
S24	CI	CI	Adaptive

S25	CI	HA	Control
S26	CI	HA	Adaptive
S27	CI	CI	Control
S28	HA	CI	Control
S29	CI	HA	Control
S30	HA	HA	Adaptive
S31	HA	HA	Adaptive
S32	HA	HA	Adaptive

APPENDIX D.5 Summary of Analyses by Device Type

A univariate analysis of variance (ANOVA) was performed on all pretraining assessment measures to determine the presence of any significant differences by device type. Children in this study were fit with two hearing aids (n = 10), two cochlear implants (n = 11), or one cochlear implant and one hearing aid (n = 11). No significant differences were revealed on the PPVT 4, any of the tasks of the NEPSY-II inhibition subtest, or the sequence learning tasks with color stimuli. For the final verbal assessment, the Children's Test of Nonword Repetition, there were no differences for the total number of words correctly produced or for correctly produced nonwords two and three syllables in length. There were, however significant differences by device for the correct production of nonwords that were four syllables in length, $p < .05$. Mean number of four syllable nonwords correctly produced was 0.55 for the group with 2 cochlear implants, 0.00 for the group with one implant and one hearing aid, and 0.90 for the two hearing aid group. Likewise for the number of correctly produced five syllable nonwords a difference by device type was revealed as well with the mean for the group with two implants, one implant and one hearing aid, and two hearing aids being 0.36, 0.46, and 1.20 respectively. For the total number of syllable errors and for errors at each syllable length there were no significant differences by device type. There were also no significant differences in performance on any of the nonverbal assessments (WRAML 2 and the sequence learning tasks with black and white color stimuli.

Following the visuspatial sequencing regimen, performance on each of the assessment measures was examined in a 3 (Device Type) x 2 (Training Condition) x 3 (Time) repeated measures ANOVA with the last factor treated as repeated measure with unequal spacing. Only one significant result was revealed on any of the assessment tasks. Analysis of the number of nonwords three syllables in length that were produced correctly revealed a significant interaction of Device Type x Time $F(2,25) = 6.45$, $p < .01$. Using Bonferroni correction, pairwise comparison showed that subjects with two hearing aids increased the number of correctly produced words from pretraining (M = 1.13) to the second posttest (M = 2.17).

The reason for improvement in production of three syllable nonwords for the subjects with hearing aids is unclear. However, the presence of just a single significant result in the analyses by hearing status among all of the pretraining to post training analyses indicates that device type did not play a major role in performance outcomes. For this reason all analyses reported in the body of this paper combined all three device types into one group of deaf or hard of hearing subjects.