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Relations between nonverbal cognitive ability and spoken language development : implications for deaf toddlers who use cochlear implants.

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RELATIONS BETWEEN NONVERBAL COGNITIVE ABILITY AND SPOKEN LANGUAGE DEVELOPMENT: IMPLICATIONS FOR DEAF TODDLERS WHO USE COCHLEAR IMPLANTS

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DEDICATION

This dissertation is dedicated to my mother

Lori Ann Canerday

who always told me I could accomplish anything I set my mind to.

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ABSTRACT

RELATIONS BETWEEN NONVERBAL COGNITIVE ABILITY AND SPOKEN LANGUAGE DEVELOPMENT: IMPLICATIONS FOR DEAF TODDLERS WHO USE COCHLEAR IMPLANTS

Carissa L. Shafto

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The first aim of this dissertation was to determine whether early deafness is related to children's nonverbal cognitive abilities. Performance of a group of deaf infants were compared to that of same-aged hearing infants on visual sequence learning (VSL) and visual recognition memory (VRM) tasks. The hypothesis was that if deafness is negatively related to general cognitive ability, then the deaf infants would perform more poorly than same-aged hearing infants on the two tasks. There were no significant differences in VSL (n = 19) or VRM (n = 13) performance between the two groups (Chapter III). These results are inconclusive due to the small sample sizes, but importantly, there were individual infants in both groups who demonstrated learning on the two nonverbal tasks.

The second aim was to determine whether VSL and VRM ability can provide predictive information about spoken language development. The results for the normal-hearing 8.5-month-olds provide evidence for a significant relation between VSL ability and spoken language outcomes (Chapter IV). Specifically, it was found that sequence learning (thought to rely on procedural memory ability) may contribute to vocabulary and gestural development in normal-hearing infants. Further research with larger samples of

infants is needed to determine whether procedural learning may be important for grammar acquisition.

These results suggest that VSL ability may not be related to spoken language outcomes for deaf infants who use cochlear implants (Chapter V), although VRM ability may be (Chapter VI). If this pattern of results held up for a larger sample of deaf infants, this would suggest that the nonverbal cognitive abilities tapped in the VSL and VRM tasks are not critical for at least some aspects of spoken language development in deaf children who use cochlear implants, and that potential deficits in nonverbal cognitive ability are not necessarily associated with poorer spoken language ability in this population. In future research a larger sample of deaf infants should be recruited in order to clarify whether nonverbal cognitive skills are related to early deafness, and how those nonverbal skills might relate to spoken language development in this unique population.

TABLE OF CONTENTS

PAGE

ACKNOWLEDGMENTS....iv
ABSTRACT....v
LIST OF TABLES....xiii
LIST OF FIGURES....xvi

CHAPTER I: GENERAL INTRODUCTION....1

Modality and Domain-General Theories of Language....3

Domain-specific processes underlying language development....6

Domain-general processes underlying language development....8

Summary....10

The Relation between Deafness and Spoken Language Development....11

Deaf oral children who use cochlear implants....14

Summary....18

The Relation between Deafness and Nonverbal Cognition....19

Deaf individuals who use manual communication....20

Deaf individuals who use oral communication and have hearing aids or cochlear implants....26

Potential mechanisms for the relation between deafness and nonverbal ability....30

Summary....31

The Relation between Nonverbal Cognition and Spoken Language Development....31

In typical development....32
In deaf children....34
Summary....35
Specific Research Questions....36
CHAPTER II: METHODOLOGY....41
Novelty Versus Familiarity Preference....41
Experimental Measures....42
Visual Sequence Learning (VSL) task....43
Apparatus....44
Stimuli....44
Procedure....45
Data collection....49
Visual Recognition Memory (VRM) task....50
Apparatus....51
Stimuli....53
Procedure....55
Data collection....56
Calculation of Effect Size....58
Language and Communication Measures....59
Words and Gestures form....59
Words and Sentences form....59
CDI data collection: 8.5-month-old infants....60
CDI data collection: Deaf infants....60
CDI dependent variables....62

Issues to consider..63
CHAPTER III: RELATION BETWEEN EARLY DEAFNESS AND NONVERBAL COGNITIVE ABILITY..65
Study 1: Visual Sequence Learning..66
Participants..66
General Procedure..67
VSL Analyses..67
VSL Results..67
Study 2: Visual Recognition Memory..75
Participants..75
General Procedure..76
VRM Analyses..76
VRM Results..77
Discussion..80
CHAPTER IV: VISUAL SEQUENCE LEARNING IN INFANCY: DOMAIN-GENERAL AND DOMAIN-SPECIFIC ASSOCIATIONS WITH LANGUAGE.........87
Method..88
Participants..88
Task Details..88
Language Measures..89
Results..89
Did Infants Learn the Sequence?..90
Does VSL Task Performance Correlate with Infants' Receptive Language Ability?..94

Does VSL Task Performance Correlate with Infants' Receptive Language Ability 5 Months after Participating in the Study?....................................96

Does VSL Task Performance Correlate with Infants' Productive Vocabulary 9 Months after Participating in the Study?...105

Does VSL Task Performance Correlate with Infants' Productive Language Ability 15 Months after Participating in the Study?.................................106

Does VSL Task Performance Correlate with Infants' Productive Language Ability 20 Months after Participating in the Study?..................................107

Discussion..109

CHAPTER V: CORRELATIONS BETWEEN VISUAL RECOGNITION MEMORY AND LANGUAGE DEVELOPMENT IN NORMAL-HEARING INFANTS..........119

Method..120

Participants..120

Task Details..120

VRM Analyses..121

Language Measures...121

Results..121

Did Infants Demonstrate Recognition Memory for the Stimuli?................122

Does VRM Task Performance Correlate with Infants' Receptive Language Ability?..127

Does VRM Task Performance Correlate with Infants' Receptive Language Ability 5 Months after Participating in the Study?......................................128

Does VRM Task Performance Correlate with Infants' Productive Language Ability 9 Months after Participating in the Study?......................................132

Does VRM Task Performance Correlate with Infants' Productive Language Ability 15 Months after Participating in the Study?....................................138

Does VRM Task Performance Correlate with Infants' Productive Language Ability 20 Months after Participating in the Study?....................................139

Summary of VRM Results...144

Discussion...149

Conclusion...151

CHAPTER VI: THE SPOKEN LANGUAGE DEVELOPMENT OF DEAF INFANTS AND ITS RELATION TO VISUAL SEQUENCE LEARNING AND VISUAL RECOGNITION MEMORY...153

Method...153

Participants...153

Experimental Measures...154

Language Measures...154

Results...155

Implantation Age Groups..155

Testing the Relation Between Experimental Task Performance and the CDI...163

Discussion...172

CHAPTER VII: GENERAL DISCUSSION...173

Specific Research Questions Revisited..174

The Correlation between VSL Ability and Receptive Vocabulary...........................178

The Correlation between VSL Ability and Productive Grammar...........................179

Domain-Generality and Modality-Specificity..181

The Role of Domain-General Processes in Language...183

Future Research...184

Summary..185

REFERENCES..187

CURRICULUM VITAE..218

LIST OF TABLES

TABLE PAGE

3-1. Demographic information for deaf participants.....68

3-2. Descriptive statistics for deaf and hearing infants on VSL task measures.....73

3-3. Descriptive statistics for deaf and hearing infants on VRM task measures.....83

4-1. Descriptive statistics for VSL task measures.....91

4-2. Descriptive statistics for CDI-1 Measures at 8.5 (n = 53) and 13.5 (n = 38) months of age.....92

4-3. Descriptive statistics for CDI-2 Measures at 17.5 (n = 36), 23.5 (n = 39), and 28.5 (n = 27) months of age.....93

4-4. Partial correlations between VSL performance and CDI-1 Measures at 8.5 Months (controlling for age at CDI).....99

4-5. Partial correlations between VSL performance and CDI-1 Measures at 8.5 months by learner status (controlling for age at CDI).....100

4-6. Partial correlations between VSL performance and CDI-1 Measures at 13.5 Months (controlling for age at CDI).....101

4-7. Partial correlations between VSL performance and CDI-1 Measures at 13.5 Months by learner status (controlling for age at CDI).....102

4-8. Correlations between VSL performance and CDI-2 vocabulary production at 17.5 (n = 36), 23.5 (n = 39), and 28.5 (n = 27) months.....103

4-9. Correlations among CDI-2 vocabulary and grammatical measures at 23.5 and 28.5 months....114

4-10. Correlations between VSL performance and CDI-2 grammatical measures at 23.5 months....115

4-11. Correlations between VSL performance and CDI-2 grammatical measures at 23.5 months by learner status....116

4-12. Correlations between VSL performance and CDI-2 grammatical measures at 28.5 months....117

4-13. Correlations between VSL performance and CDI-2 grammatical measures at 28.5 months by learner status....118

5-1. Descriptive statistics for VRM task measures....124

5-2. Descriptive statistics for the CDI-1 measures at 8.5 and 13.5 months....125

5-3. Descriptive statistics for the CDI-2 measures at 17.5, 23.5, and 28.5 months....126

5-4. Correlation matrix for the CDI-1 measures at 8.5 months....131

5-5. Correlation matrix for the CDI-1 measures at 13.5 months....136

5-6. Correlation matrix for CDI-2 vocabulary production at 17.5, 23.5, and 28.5 months....137

5-7. Correlation matrix for the CDI-2 grammatical measures at 23.5 months....140

5-8. Correlation matrix for the CDI-2 grammatical measures at 28.5 months....145

6-1. Counts for CDIs returned at each of the post-cochlear implantation time points...156

6-2. Results from the growth curve analyses between the VSL task and CDI-1 vocabulary comprehension score....160

6-3. Results from the growth curve analyses between the VSL task and CDI-1 total gestures score....161

6-4. Results from the growth curve analyses between the VSL task and CDI-2 vocabulary production....162

6-5. Results from the growth curve analyses between the VRM task and CDI-1 vocabulary comprehension score....169

6-6. Results from the growth curve analyses between the VRM task and CDI-1 total gestures score....170

6-7. Results from the growth curve analyses between the VRM task and CDI-2 vocabulary production score....171

LIST OF FIGURES

FIGURE PAGE

2-1. Sound booth set-up for the Visual Sequence Learning task....................................46

2-2. Stimuli sets for the Visual Sequence Learning task...47

2-3. Sound booth set-up for the Visual Recognition Memory task...............................52

2-4. Stimuli sets for the Visual Recognition Memory task...54

2-5. Example of a test phase with span length 3 in the Visual Recognition Memory task
....57

3-1. RT difference score on the VSL task for individual infants....................................71

3-2. Correct anticipatory looks in phases 1 and 2 of the VSL task for individual infants..72

3-3. RT difference score on the VSL task as a function of age at test..............................74

3-4. Novelty score across the span-2 test trials of the VRM task for individual infants...81

3-5. Novelty score across the span-3 test trials of the VRM task for individual infants...82

3-6. Average novelty score on the span-2 test trials of the VRM task as a function of age at test..84

3-7. Average novelty score on the span-3 test trials of the VRM task as a function of age at test..85

4-1. Scatterplots for CDI-1 Vocabulary Comprehension scores at 8.5 months and 13.5 months, with the RT Difference Score...97

4-2. Scatterplots for CDI-1 Gesture Comprehension scores at 8.5 months and 13.5 months, with the RT Difference Score....................98

4-3. Scatterplot for CDI-2 Corrected Vocabulary Production score at 17.5 months, with the RT Difference Score....................104

4-4. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 23.5 months and 28.5 months, with the RT Difference Score....................111

4-5. Scatterplots for CDI-2 Inflection scores at 23.5 months and 28.5 months, with the RT Difference Score....................112

4-6. Scatterplots for CDI-2 Irregulars scores at 23.5 months and 28.5 months, with the RT Difference Score....................113

5-1. Scatterplots for CDI-1 Vocabulary Comprehension scores at 8.5 months and the VRM Novelty Scores....................129

5-2. Scatterplots for CDI-1 Gesture Comprehension scores at 8.5 months and the VRM Novelty Scores....................130

5-3. Scatterplots for CDI-1 Vocabulary Comprehension scores at 13.5 months and the VRM Novelty Scores....................133

5-4. Scatterplots for CDI-1 Gesture Comprehension scores at 13.5 months and the VRM Novelty Scores....................134

5-5. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 17.5 months and the VRM Novelty Scores....................135

5-6. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 23.5 months and the VRM Novelty Scores....................141

5-7. Scatterplots for CDI-2 Inflection scores at 23.5 months and the VRM Novelty Scores......142

5-8. Scatterplots for CDI-2 Irregulars scores at 23.5 months and the VRM Novelty Scores......143

5-9. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 28.5 months and the VRM Novelty Scores......146

5-10. Scatterplots for CDI-2 Inflection scores at 28.5 months and the VRM Novelty Scores......147

5-11. Scatterplots for CDI-2 Irregulars scores at 28.5 months and the VRM Novelty Scores......148

6-1. Deaf children's individual vocabulary comprehension scores from the CDI-1.....157

6-2. Deaf children's individual gestures scores from the CDI-1......158

6-3. Deaf children's individual vocabulary production scores from the CDI-2......159

CHAPTER I

GENERAL INTRODUCTION

Broadly, my research goal is to delineate the factors underlying the variability in spoken language outcomes in deaf children who use cochlear implants. This dissertation is one step toward that goal. It is well-established in the literature that deafness is negatively related to spoken language development (e.g., Davis, 1974; Geers, Kuehn, & Moog, 1981; Geers & Moog, 1994; Geers, Moog, & Schick, 1984; Geers & Tobey, 1995; Levitt, McGarr, & Geffner, 1987; Moeller, Osberger, & Eccarius, 1986; Osberger et al., 1991; Osberger, Moeller, Eccarius, McConkey Robbins, & Johnson, 1986; Tyler et al., 1997; Waltzman et al., 1990). However, we do not know the extent to which deafness is related to spoken language directly—via modality-specific and domain-specific processes—or whether deafness is also related to spoken language development indirectly—via general cognitive abilities or domain-general processes.

Deafness can relate to language via general cognitive abilities only to the extent that there are relationships between general cognitive abilities and spoken language, and that deafness is related to general cognitive abilities. This raises two issues: 1) Is there a relation between deafness and general cognitive abilities? 2) What is the relationship between general cognitive abilities and spoken language development? In response to these two questions, this dissertation addresses five specific research questions.

1). Is early deafness related to the nonverbal cognitive abilities (i.e., visual sequence learning and visual recognition memory) of deaf infants?

2). Does visual sequence learning ability (one nonverbal cognitive ability) relate to spoken language development in normal-hearing infants?

3). Does visual recognition memory ability (one nonverbal cognitive ability) relate to spoken language development in normal-hearing infants?

4). Does visual sequence learning ability relate to spoken language development in deaf infants who use cochlear implants?

5). Does visual recognition memory ability relate to spoken language development in deaf infants who use cochlear implants?

In order to set the background for these five specific research questions, the General Introduction includes sections on modality and domain-general theories of language acquisition, the relation between deafness and spoken language development, the relation between deafness and nonverbal cognition, and the relation between nonverbal cognition and spoken language development. In each section findings from studies of different populations of deaf children and adults are reviewed. This includes findings from studies of deaf signers as well as from studies of deaf children who use hearing aids or cochlear implants, to the extent that there is published literature on each population. The population of interest for this dissertation is deaf children who use oral communication and who have parents with typical hearing ability and throughout this dissertation the term 'deaf' refers to individuals with profound hearing loss (usually greater than 90 dB HL). Individuals with this level of hearing loss have traditionally received little benefit from hearing aids and at the present time are typically eligible to receive a cochlear implant.

Modality and Domain-General Theories of Language

Language acquisition depends on the development of fundamental linguistic and cognitive processes. Because of the range of variability in language skills that exists across both healthy individuals and various clinical populations, being able to pinpoint specific cognitive processes that give rise to such variability can have important theoretical and potentially clinical implications. In this section four kinds of processes that may relate to spoken language development are discussed: (1) domain- and modality-general processes, (2) domain- and modality-specific processes, (3) domain-general / modality-specific processes, and (4) domain-specific / modality-general processes. For the purposes of this dissertation, the definition of "domain" is taken directly from Karmiloff-Smith (1992, p. 6), where a domain is "the set of representations sustaining a specific area of knowledge: language, number, physics, and so forth." A domain-specific process is defined as one that is dedicated to learning about a particular domain of knowledge and a domain-general process is one that invokes parallel learning processes across different domains (see Saffran & Thiessen, 2007).

A domain- and modality-general process underlying spoken language (1) would be evidenced by, for example, a correlation between infant visual sequence learning and spoken language outcomes such as vocabulary ability (e.g., Conway, Bauernschmidt, Huang, & Pisoni, 2010; Shafto, Conway, Field, & Houston, 2012). A domain- and modality-specific process underlying spoken language (2) would be evidenced by, for example, a correlation between infant speech segmentation and spoken language outcomes (e.g., Tsao, Liu, & Kuhl, 2004). A modality-specific / domain-general process underlying spoken language (3) would be evidenced by, for example, a correlation between auditory sequence learning of non-linguistic stimuli (e.g., tones) and spoken language outcomes (see Conway & Pisoni, 2008). A modality-general / domain-specific process underlying spoken language (4) would be evidenced by, for example, a correlation between infant sign language acquisition and spoken language outcomes. The background for these four different processes is now reviewed.

There are two major theories of the origins of infants' knowledge. One suggests that infants obtain knowledge via domain-specific processes (e.g., Baillargeon, 2001; Gelman, 1990; Leslie, 1995; Mandler, 1992; Meisel, 1995; Premack, 1990; Spelke, 1994, 2004; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke & Kinzler, 2007; Wynn, 1992; Xu & Garcia, 2008). The domain-specific processes are typically thought to be either innate or available from a very early age. Much of the recent evidence for domain specificity has come from research by Spelke and colleagues in the domains of object representation, agency, number, and geometry (see Spelke & Kinzler, 2007 for review).

The second theory posits that infants obtain knowledge about the world via domain-general processes (e.g., Bates, 1994; Colunga & Smith, 2005; Kirkham, Slemmer, & Johnson, 2002; Madole & Oakes, 1999; Quinn & Eimas, 1997; Rakison & Lupyan, 2008; Rakison & Yermolayeva, 2011; Rogers & McClelland, 2004; Saffran, Pollak, Seibel, & Shkolnik, 2007; Smith, Jones, & Landau, 1996; Thiessen, 2011). A recent commentary cites studies of N- or U-shaped development in the domains of objects and language, as evidence for domain-general processes in perceptual and cognitive development (see Rakison & Yermolayeva, 2011 for detailed discussion). In particular, Rakison and Yermolayeva argued that similar developmental trajectories have been demonstrated across a variety of domains, and thus represent processes that are domain-general. The cited evidence comes from behavioral studies on infants' learning of object properties, faces, language, and gesture, as well as Event-Related Potential studies. If language is underwritten by one or more domain-general processes, then the same information processing abilities that contribute to nonlinguistic cognitive abilities should also contribute to language development (Hollich, Hirsh-Pasek, & Golinkoff, 2000). Clinically this is important because understanding how nonlinguistic cognitive abilities relate to language development could provide valuable information about possible causes (processes) underlying language delays and disorders.

In addition to domain, the *modality* of information may also be important for learning. Behavioral evidence suggests that statistical sequential learning is constrained by the sense modality in which the input patterns occur, with auditory learning proceeding in substantially different ways compared to visual or tactile learning. In particular, in a series of studies with tactile, auditory, and visual sequential learning tasks, adults were better at learning auditory sequences compared to the other two modalities (Conway & Christiansen, 2005; Emberson, Conway, & Christiansen, 2011). Furthermore, there were qualitative differences in learning across the modalities, with audition affording better memory for the final components of the sequences (Conway & Christiansen, 2005). This behavioral evidence is supported by neuroimaging data showing that implicit learning is largely mediated by modality-specific unimodal processing mechanisms (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Turk-Browne, Scholl, Chun, & Johnson, 2009).

Importantly, a combination of domain-generality and modality-specificity appears to characterize language. For instance, both reading and listening tasks involve a common phonological network of brain regions, including the inferior frontal area, whereas visual and auditory unimodal and association areas have been found to be preferentially active during reading and listening tasks, respectively (Jobard, Vigneau, Mazoyer, & Tzourio-Mazoyer, 2007). Next the evidence for domain-specific and domain-general processes underlying language ability is reviewed, keeping in mind that modality may influence those relations.

Domain-specific processes underlying language development. A domain-specific process is one that is invoked across different tasks within a domain. For example, in the domain of (spoken) language, a modality- and domain-specific process is one that is utilized across different kinds of auditory speech tasks. There is a growing body of research tying various early speech processing abilities to later vocabulary abilities. For example Tsao and colleagues (2004) measured children's speech discrimination abilities at 6 months of age, then at 13, 16, and 24 months of age had parents fill out the MacArthur-Bates Communicative Development Inventory (CDI) (Fenson et al., 1993) as a measure of their child's vocabulary. They found significant positive correlations between speech discrimination ability at 6 months of age and vocabulary ability at each of the later time points, suggesting a predictive link between speech discrimination in infancy and vocabulary development during the second year of life (see also Benasich & Tallal, 2002; Vance, Rosen, & Coleman, 2009). This is consistent with an interpretation where there are common processes underlying these skill sets, although these results do not discount a domain-general explanation.

Another piece of evidence for a relation between early speech perception and later language (i.e., domain-specific processes) was reported by Newman, Bernstein Ratner, Jusczyk, Jusczyk, and Dow (2006). Newman and colleagues retrospectively analyzed infants' early speech processing performance and later language abilities, specifically measuring speech stream segmentation, language discrimination, and prosodic bootstrapping abilities. Children were originally tested as infants on the various tasks and a child's 'successes' or 'failures' were used to quantify their early speech processing ability. The children were brought back into the lab when they were 2 years old, contrasting children with expressive vocabularies in the top 15% to the bottom 15%. The results suggested that children with larger vocabularies as toddlers had generally been more successful at the speech processing tasks as infants than those children with smaller vocabularies as toddlers (the bottom 15%) and this pattern of results was the strongest for the speech segmentation task.

Because many children with low vocabularies at age 2 manage to catch-up to their peers by 3 or 4 years old (L. B. Leonard, 1997; Rescorla & Lee, 2000), Newman and colleagues included a follow-up of the same children when they were between 4 and 6 years old. Children were classified as either 'segmenters' or 'non-segmenters' based on their speech discrimination performance as an infant. They were then compared (as groups) on language and articulation, general cognitive abilities, and a parental report of communicative competence. The results suggested that children who successfully segmented speech streams during infancy and had high vocabularies at age 2 remained relatively advanced in their English language abilities two years later (Newman et al., 2006). A number of other studies have also found that speech and language abilities measured in infancy predict later language development (e.g., Fernald, Perfors, & Marchman, 2006; Junge, Kooijman, Hagoort, & Cutler, 2012; Marchman & Fernald, 2008; Singh, Reznick, & Xuehua, 2012).

Domain-general processes underlying language development. There is also evidence for domain-general processes underlying language development. A domain-general process is one that is invoked across different domains (Saffran & Thiessen, 2007). For example, a modality- and domain-general process could be expressed in analogous ways for both auditory speech and visual stimuli. Some examples include recognition memory and speed of processing, which are discussed below. In general, a substantial amount of empirical research has demonstrated a strong link between nonverbal and verbal cognitive abilities (e.g., Plomin & Dale, 2000; although for one recent exception, see Newman et al., 2006).

Visual recognition memory, for one, has been found to be correlated with cognitive and linguistic outcomes (e.g., Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; Fagan & McGrath, 1981; Rose, Feldman, & Jankowski, 2009, 2012). Rose and colleagues have argued that children's abstraction of perceptual features forms the basis for their concepts of objects and that those concepts need to be in place before language may be acquired (Rose, Feldman, Wallace, & Cohen, 1991). In addition to recognition memory, working memory (L. B. Leonard et al., 2007) and speed of processing during a variety of non-linguistic tasks (C. A. Miller, Kail, Leonard, & Tomblin, 2001) have been found to explain language ability in children with language impairment.

Habituation rate is also found to relate to language outcomes. Habituation is thought to involve encoding, which is a form of learning (see R. F. Thompson, 2009 for a historical review; see R. F. Thompson & Spencer, 1966 for a classic paper on habituation). Specifically, habituation to a stimulus is thought to reflect a decline in information processing—due to the stimulus being sufficiently encoded—rather than sensory fatigue. Studies on infant habituation rate and novelty preference have demonstrated a link between attention and cognitive outcomes, such that shorter looking times (i.e., faster information processing) were indicative of better vocabulary growth (Colombo et al., 2004; McCall & Carriger, 1993). Other studies of infant attention have found similar results (see e.g., Kannass & Oakes, 2008; L. Thompson, Fagan, & Fulker, 1991). Taken together, these studies all suggest a positive relationship between the domain-general processes of memory, habituation, and attention, with language development.

Another type of domain-general process that may be important for language development is sequence learning, a type of procedural or non-declarative memory (Clegg, DiGirolamo, & Keele, 1998). Sequence learning is the process of acquiring knowledge about complex sequential stimulus patterns in virtually any domain (music, speech, visual patterns, etc.), usually occurring under conditions without conscious intent or awareness (Berry & Dienes, 1993; Cleeremans & McClelland, 1991). This kind of learning is often studied using 'implicit learning' and 'statistical learning' tasks. Although they are referred to with different terms, there is growing consensus that they may actually reflect the same underlying phenomenon (Perruchet & Pacton, 2006). For instance, Boyer and colleagues (Boyer, Destrebecqz, & Cleeremans, 2005) argued that implicit sequence learning is a type of statistical learning in that it involves "simple associative prediction mechanisms" (p.383).

Statistical learning involves (implicitly) tracking co-occurrence statistics among distributed elements (often occurring in sequence). For example, Saffran and colleagues found that 8-month-old infants' responses during a statistical-learning task suggested that they can incidentally learn relatively complex co-occurrence statistics—specifically, transitional probability information—from a continuous speech stream (Saffran, Aslin, & Newport, 1996). Similar results have emerged from studies using non-linguistic auditory stimuli such as tones (Saffran, Johnson, Aslin, & Newport, 1999).

While early studies focused on statistical learning using auditory stimuli, many subsequent studies have demonstrated statistical learning abilities in infants and adults using visual stimuli. For instance, Kirkham et al. (2002) found that 2-, 5-, and 8-month-old infants were able to learn statistically predictable sequences of visual stimuli in a manner that appeared to be analogous to statistical learning with speech stimuli (see also Fiser & Aslin, 2002; Johnson et al., 2009; Kirkham, Slemmer, Richardson, & Johnson, 2007).

Summary. Domain-specific and domain-general theories predict differential relations between cognitive and linguistic abilities. We do not know whether the spoken language difficulties that deaf children encounter are due to direct deficits in domain-specific and modality-specific (i.e., auditory) processes, or whether they might be due to indirect deficits in domain- and modality-general (i.e., general cognitive) processes.

My ultimate research goal is to identify the factors underlying the variability in spoken language outcomes in deaf children who use cochlear implants, so in the next section the existing literature on the spoken language development of deaf children is reviewed. The empirical results in subsequent chapters are examined in light of both domain-specific and domain-general theories in order to estimate the extent to which deafness is related to spoken language directly—via modality-specific and domain-specific processes—or indirectly—via general cognitive or domain-general processes.

The Relation between Deafness and Spoken Language Development

In the US about 2 to 3 out of every 1,000 children are born deaf or hard-of-hearing and about 90% of those children are born to parents who have typical hearing ability (National Institute on Deafness and Other Communication Disorders, 2011). That means that only about 10% of the children in the US who are born deaf have parents who are also deaf, and thus have potential access to sign language (typically American Sign Language, or ASL) in the home. In order to understand how deafness relates to spoken language development, one must first consider the goals and decisions of the family. Some families opt to use sign language for communication, so those children's spoken language development is typically little to none. In families who opt to use spoken language for communication, some have tried an oral-only approach and some have tried total communication (which are both described later in this chapter). The effects of these different choices on spoken language development also depend on the technology used. The following sections discuss the findings for children who used the different communication approaches before cochlear implantation was available and in the years since cochlear implantation has been widely available to young children.

The two dominant communication modes for deaf children born to hearing parents are oral-only communication and total communication. Oral-only communication relies entirely on oral and aural cues. Total communication relies on simultaneously presenting oral/aural and manual cues. The manual cues in total communication vary, but are most commonly manually-coded English (known as Signed Exact English; SEE) and are not ASL signs.

Going back to the 1970s and 1980s there is a great deal of evidence that deaf children with deaf parents who use ASL acquire ASL in a fashion that is similar to typical spoken language acquisition in hearing children (e.g., Bellugi & Klima, 1982; Collins-Ahlgren, 1975; Meier, 1982; Newport & Ashbrook, 1977). The results of these studies encouraged the widespread use of total communication because it was thought that deaf children could more easily acquire a communicative system through the manual modality. However, the results of several subsequent studies focusing on the English language abilities of deaf children who used total communication (e.g., Geers et al., 1984) suggested that deaf children were largely unsuccessful at mastering spoken English.

Prior to the 1990s, deaf children who used oral communication or total communication were shown to demonstrate significant delays in all areas of spoken language (Davis, 1974; Geers et al., 1981; Geers et al., 1984; Levitt et al., 1987; Moeller et al., 1986; Osberger et al., 1986). In those early studies the English abilities of deaf children were found to develop at a significantly slower pace than children with typical hearing ability. Because the majority of deaf children are born to hearing parents (who usually only know a spoken language), most of the research has focused on deaf children using oral-only communication.

One such study investigated spoken language ability in 168 deaf oral children who used hearing aids and oral-only communication (Geers et al., 1984). The deaf children only scored higher than 70% correct on a few subtests of basic syntactic ability: nouns, verbs, and wh-question words. However, 26 of the children had overall scores greater than 85% correct, suggesting that at least some of the children were able to acquire spoken English. In addition, these deaf children were compared to a group of deaf children who used total communication, and the oral-only children performed significantly better than the total communication group on almost all of the subtests of the Grammatical Analysis of Elicited Language-Simple Sentence Level (GAEL-S; Moog & Geers, 1979).

Since this early study was completed, several studies have found deaf children in total communication programs to acquire better spoken language ability compared to deaf children in oral-only programs (Coerts, Baker, van den Broek, & Brokx, 1996; Coerts & Mills, 1995), even for those deaf children who had received a cochlear implant (Connor, Heiber, Arts, & Zwolan, 2000). However, more recent studies (of children who use cochlear implants) have found either no difference in spoken language performance between deaf children in total communication and oral-only programs (McConkey Robbins, Bollard, & Green, 1999), or superior English abilities in children using oral-only communication (Geers, Nicholas, & Sedey, 2003; Geers & Sedey, 2011; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2002). Thus the more recent research, which is likely more representative of more recently implanted children (who are largely receiving their cochlear implants prior to 2 years old), suggests that oral-only communication programs might lead to better spoken language outcomes for deaf children.

Deaf oral children who use cochlear implants. Since the 1990s cochlear implants have been available for deaf children who previously only had access to sound via tactile or hearing aids. Profoundly deaf children who use cochlear implants are a unique group of spoken language learners. They begin acquiring spoken language at an older age than typical infant learners because they cannot fully pursue spoken language acquisition until after they receive a cochlear implant. In the US, cochlear implantation is sometimes performed on children as young as 6 months of age (even younger in some other countries), but is more commonly performed on children between 12 and 24 months old. In addition, due to variability in the ages that deafness is identified, the age range when these deaf oral children begin acquiring spoken language is much wider compared to typically-hearing infant language learners, who all begin acquiring spoken language at birth (if not before). According to the National Institute on Deafness and Other Communication Disorders (NIDCD), as of 2010 at least 25,500 children in the US had received a cochlear implant (NIDCD, 2011), half of whom were implanted before the age of 6 years old. The FDA lowered the minimum age for cochlear implantation from 2 years to 12 months in the year 2000, and the average implantation age for deaf children has almost certainly decreased. There are no recent statistics on NIDCD's website regarding the average age of implantation, but over the course of this dissertation project the average implantation age has gone from 2 or 3 years old down to around 18 months.

Even the first cochlear implants (implanted in the 1990s), which were analog and had very few channels, were found to improve spoken language development in deaf children beyond what was seen with earlier assistive listening devices (Geers & Tobey, 1995; Osberger et al., 1991; Tyler et al., 1997; Waltzman et al., 1990). In one study comparing early cochlear implant users to deaf children using tactile aids or hearing aids, the children with cochlear implants demonstrated the greatest gains in English vocabulary and syntax over a three year period (Geers & Moog, 1994). Notably, their abilities after three years of cochlear implant use were similar to children with pure-tone average thresholds (PTA) of 90-100 dB HL who used conventional hearing aids, which was a dramatic improvement at the time. McConkey Robbins and colleagues followed deaf children during their first year of implant use and found a similar pattern of results, in which the receptive and expressive language abilities of deaf children with cochlear implants exceeded those of deaf children with profound hearing loss who used tactile aids or hearing aids (McConkey Robbins, Svirsky, & Kirk, 1997). Several more recent studies have found similar patterns of results when comparing cochlear implant users to hearing aid users (see also Svirsky, McConkey Robbins, Kirk, Pisoni, & Miyamoto, 2000; Tomblin, Spencer, Flock, Tyler, & Gantz, 1999).

Although deaf children with cochlear implants acquire spoken language faster than children with similar degrees of hearing loss but who use hearing aids or tactile devices, they still acquire spoken language at a slower rate than hearing children (Blamey, 2003). Deaf children usually begin spoken language acquisition with a delay due to the later onset of acquisition. When this delay in spoken language acquisition is combined with a slower rate of spoken language development, deaf children demonstrate great difficulty catching up to their hearing peers. However, predicted spoken language outcomes for deaf children with cochlear implants are improving. This is due to younger implantation ages, improved technology, earlier identification because of Newborn Hearing Screening, and likely other factors. Therefore the expectations for deaf children with cochlear implants are rising and, as a result, the outcome measures used to determine their spoken language ability are often the same outcome measures used with hearing children, such as the Reynell Developmental Language Scales (Reynell & Huntley, 1985), the Clinical Evaluation of Language Fundamentals (CELF-4) (Semel, Wiig, & Secord, 2003), and the Peabody Picture Vocabulary Test (PPVT-IV) (Dunn & Dunn, 2007).

A study of 153 deaf children with cochlear implants found that more than half of the children had age-appropriate vocabulary ability by the time they were in kindergarten, but that many fewer had caught up in other areas of spoken language (e.g., syntax) (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). Even more recently, a study of deaf adolescents who had received a cochlear implant between 2 and 5 years old found that 68% to 74% of the teens had spoken language outcome scores within a standard deviation of the test norms on tests of verbal intelligence and English vocabulary (Geers & Sedey, 2011). These studies (and others) have suggested that cochlear implants enable many deaf children to acquire spoken language abilities that are on par with their hearing peers (Dettman, Pinder, Briggs, Dowell, & Leigh, 2007; Geers, Tobey, Moog, & Brenner, 2008; Holt & Svirsky, 2008; Nicholas & Geers, 2007), but that there is an incredible amount of variability within the population (e.g., Pisoni et al., 2008).

One definitive finding that has emerged from this body of work is that there are several major factors influencing cochlear implant users' ultimate language outcomes. Aside from changes in cochlear implant technology (e.g., Geers, 2006), implantation age is perhaps the most commonly studied factor in cochlear implant users' spoken language outcomes. There is evidence both for and against the potential effect of implantation age on speech and language development in children with cochlear implants. Tobey and colleagues did not find a significant effect of implantation age in a group of deaf children who received their cochlear implants between 2 and 5 years old (Tobey, Geers, Brenner, Altuna, & Gabbert, 2003) and Geers (2004) found no significant relations between implantation age and speech and language outcomes for a group of children implanted between the ages of 2 and 4 years. Because the children in both of these studies were between 2 and 5 years old, it is possible that any effects of implantation age are at even younger ages (e.g., before the age of 2 or 3 years).

In fact, in one recent study a comparison of toddlers and preschoolers with cochlear implants found that children implanted before 2 years of age had significantly higher receptive and expressive spoken language ability when compared to children implanted between 2 and 3 years old (Miyamoto, Hay-McCutcheon, Kirk, Houston, & Bergeson, 2008). Tomblin and colleagues tested a group of children with cochlear implants who were implanted between 11 and 40 months of age and found a beneficial effect of earlier implantation age (as a continuous variable) on expressive language abilities (Tomblin, Barker, Spencer, Zhang, & Gantz, 2005). Nicholas and Geers (2007) also found significant implantation age effects in that children implanted before the age of 16 months were more likely to reach age-appropriate spoken language abilities by 4.5 years old than children implanted after 16 months. Colletti et al. (2011) found significant advantages in later expressive and productive spoken language abilities for infants who received a cochlear implant prior to 12 months old. They also showed significantly better nonverbal cognitive abilities compared to children implanted between 12 and 23 months, and compared to children implanted between 24 and 35 months of age. Taken together, these results suggest that there are effects of implantation age and that cochlear implants may have maximal beneficial effects if received before a child's second birthday (see also Dettman et al., 2007; Geers et al., 2009; Holt & Svirsky, 2008; Svirsky, Chin, & Jester, 2007; Svirsky, Teoh, & Neuburger, 2004; Vlastarakos et al., 2010), although the jury is still out regarding exactly when the so-called sensitive period starts to close, which may be at an even younger age.

In addition to age at implantation, several other factors have been found to significantly correlate with child cochlear implant users' spoken language outcomes, including communication mode (Geers, 2006; Geers & Sedey, 2011), maternal engagement in parent-child interaction (Niparko et al., 2010), family socioeconomic status or SES (Geers, 2006; Niparko et al., 2010), age of deafness onset (Geers, 2006), and pre-implant residual hearing level (Niparko et al., 2010). Early identification of hearing loss is another, although Hammes and colleagues (Hammes et al., 2002) found that early identification and early amplification were not sufficient interventions, as early implantation still led to better spoken language outcomes. Pisoni et al. (2008) reviewed findings from their own lab and others and reported several key findings with regard to outcome and benefit for children following cochlear implantation. Specifically, they reported that there are usually large individual differences in outcomes across participants within a group, there are relations with implantation age, there are relations with early experience via communication mode, and there are links between speech perception and production, but thus far no pre-implant *behavioral* predictors of outcomes.

Summary. In summary, evidence suggests that spoken language development is poorer both in deaf individuals who use total communication and in deaf individuals who use oral-only language to communicate. Despite increased identification of several different characteristics that relate to spoken language outcome in the studies reviewed here, there is still a great deal of unexplained variability – in particular, in the outcomes of children who use cochlear implants. Reducing the myriad other potential factors that may influence these children's spoken language development was one motivation for this dissertation. In particular, I aimed to gather data on whether visual sequence learning and/or visual recognition memory are behavioral predictors of spoken language outcome in deaf children who use cochlear implants. There are currently no published studies on the nonverbal abilities of deaf *infants*, and no studies on visual recognition memory ability in deaf children of any age. In the next section I review what is known about the nonverbal cognitive abilities of deaf children.

The Relation between Deafness and Nonverbal Cognition

Going back to Piaget (e.g., 1969), it has been suggested that intelligence may develop in part through sensory-motor activities in infancy (see also e.g., Newcombe, 2011 for more recent theories that build on this idea). This begs the question of how cognitive abilities develop in children who experience early sensory deprivation such as deafness.

Evidence from neuroscience suggests that a lack of sensory input leads to cortical reorganization for the intact senses (e.g., Fine, Finney, Boynton, & Dobkins, 2005; Merzenich et al., 1984). However, sensory deprivation in one domain (e.g., audition) does not always lead to reorganization of other sensory representations (e.g., vision). For example, deaf individuals demonstrate brightness discrimination and contrast sensitivity that is similar to that of hearing individuals (Bross, 1979; Finney & Dobkins, 2001).

Similarly, a prevailing view of deafness is that auditory deprivation affects spoken language development, but not more general cognitive abilities (e.g., Braden, 1994; McConkey Robbins, 2006). However, research on children with congenital cataracts – who experience early visual deprivation – suggests that early sensory deprivation could also be related to differences in *cognitive* development. In particular, work by Maurer and colleagues has found that, in addition to atypical development of visual acuity, early visual deprivation is also associated with atypical processing of faces (see Maurer, Mondloch, & Lewis, 2007 for review). This warrants a similar investigation in infants who experience early auditory deprivation.

In keeping with traditional views of deafness Braden (1988) conducted a review of the literature which suggested that auditory deprivation "exerts a barely noticeable effect on the nonverbal IQ of deaf children" (p. 275) compared to hearing children. These studies focused on deaf children using oral-only or total communication, but in a recent review of deaf children who were ASL signers, Miller (2008) reported results from a variety of tasks tapping different aspects of intelligence, all of which resulted in nonsignificant differences between deaf signers and hearing children. Taken together, these studies support the traditional view that there are no effects of deafness on non-auditory domains. However, a growing body of research on various nonverbal abilities in both deaf oral and deaf signing individuals suggests that deafness may not just relate to poorer spoken language ability, but may negatively relate to a broader set of abilities (e.g., Marschark & Hauser, 2008).

Deaf individuals who use manual communication. In line with traditional views of deafness, there are many studies that demonstrate no difference on the nonverbal task performance of deaf adult signers compared to hearing individuals. One recent study compared deaf adult signers to a hearing control group on five different tasks of visuospatial processing that primarily involved drawing, including the Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery, 1997), and found no significant differences in performance between the two groups (Hauser, Cohen, Dye, & Bavelier, 2007). In a study of visual search, deaf and hearing adults showed no difference in their ability to detect a visual target ("Q") among visual distracters (e.g., "O") (Stivalet, Moreno, Richard, Barraud, & Raphel, 1998; see also Rettenbach, Diller, & Sireteanu, 1999). Studies of visual orienting have yielded similar results (Parasnis, 1992; Parasnis & Samar, 1985). Another study comparing deaf adult signers and hearing adults found no difference in visual enumeration or multiple object tracking ability between the two groups (Hauser, Dye, Boutla, Green, & Bavelier, 2007). In addition, studies focusing on visual sensory measures have consistently found that deaf and hearing individuals do not differ. These include studies of brightness discrimination (Bross, 1979), contrast sensitivity (e.g., Finney & Dobkins, 2001), visual temporal discrimination (e.g., Bross & Sauerwein, 1980), motion direction detection (e.g., Bosworth & Dobkins, 1999), sensitivity to motion velocity (Brozinsky & Bavelier, 2004), and tactile frequency discrimination (Levanen & Hamdorf, 2001).

There has been a great deal of research over the last 20 years investigating differences in the nonverbal abilities of deaf signing individuals compared to hearing individuals. Some of these studies have found deaf signers to perform worse on nonverbal tasks compared to hearing individuals. Other studies have found deaf signers to perform better on visual tasks compared to hearing individuals. Many studies using physiological measures have simply found differences in physiological responses for deaf compared to hearing individuals. These three kinds of studies – in which deaf signers performed more poorly than hearing peers, deaf signers performed better, and deaf signers demonstrated differential physiological responses – are now reviewed in turn. Most of this research has been done with adults, but studies of children are also reviewed where available.

Poorer performance in the deaf. Perhaps the first study to demonstrate poorer performance by deaf individuals in a nonverbal domain was one by Myklebust and Brutten (1953). They compared the visual perception abilities of 55 deaf children aged 8 to 11 years to same-aged hearing children. Children were tested on a series of visual tasks, including pattern construction using a marble board, producing line drawings, discriminating figure from ground in line drawings, and pattern reproduction using a pencil. They found that deaf children performed worse on visual patterns—both on the marble board and using a pencil to draw them—and on figure-ground discrimination. The authors suggested that deafness led to an absence of sensory integration, which was responsible for the poorer performance. All of the deaf children in that study attended a deaf school, but only 9 out of the 55 relied on manual communication. It is therefore possible that the deaf children performed worse because of their poorer language skills, rather than as a result of auditory deprivation. This is an issue returned to later in this section and in the General Discussion (Chapter VII).

An early study reported by Tomlinson-Keasey and Smith-Winberry (1990) compared deaf signing and hearing children on information processing tasks and found that despite non-significant differences in performance on three of the four tasks, the deaf children performed significantly worse on a task that required recalling sequentially-presented digits. A study of short-term memory by Boutla and colleagues found that deaf adult signers exhibited shorter digit spans than hearing controls (Boutla, Supalla, Newport, & Bavelier, 2004), although in a more recent study they found that these differences were no longer present when the temporal component (i.e., order) was removed (Bavelier, Newport, Hall, Supalla, & Boutla, 2008).

More recently, several studies have reported deficits in nonverbal skills for deaf native signers (who have fluent language) compared to hearing controls. In particular, there are several studies demonstrating poorer visual attention in the central visual field for deaf signing individuals. Proksch and Bavelier (2002) tested deaf signing adults and hearing controls on a visual response competition task involving either a central distracter or a peripheral distracter. They found that deaf signers were faster to respond than hearing adults when there was a peripheral distracter and slower than the hearing adults when there was a central distracter. Proksch and Bavelier also tested hearing adults who were native signers, and found that they performed similarly to the hearing non-signers. This suggests that the difference in performance was not due to the use of a visual language (i.e., ASL), but rather to auditory deprivation. Parasnis and colleagues found a similar pattern of results on a standardized assessment of attention (Parasnis, Samar, & Berent, 2003), but did not report the communication mode of their deaf participants.

Superior performance in the deaf. In contrast to the studies demonstrating deficits in visual abilities for deaf signing individuals, there are many studies which have found that deaf signing individuals perform better than hearing controls on nonverbal tasks. In particular, attention in the peripheral visual field seems to be enhanced in deaf signers (see Bavelier, Dye, & Hauser, 2006 for discussion). In a study using the Useful Field of View (UFOV) Dye and colleagues found enhanced visual peripheral attention in deaf adult signers compared to hearing adults (Dye, Hauser, & Bavelier, 2009). However, they found that deaf signing children did not show enhanced performance until after they were 11 years old, suggesting a development of visual attention over time. Importantly, this enhanced peripheral processing does not seem to be present in hearing individuals who are native signers (e.g., Bavelier et al., 2001; Fine et al., 2005; Neville & Lawson, 1987a; Neville & Lawson, 1987b; Proksch & Bavelier, 2002). This suggests that the processing difference is most likely due to deafness, rather than the use of a visual-manual language such as ASL.

Differential physiological responses in the deaf. While much of the behavioral research has focused on whether deaf signing individuals perform more poorly or better on nonverbal tasks than hearing individuals, physiological studies have explored whether brain activity patterns during nonverbal tasks are similar for deaf signing and hearing individuals. One study compared hearing adults to both deaf signers and hearing adult native signers in an fMRI study (Bavelier et al., 2001). The authors were interested in the effect of early auditory deprivation and/or the use of sign language on the areas of the brain that process visual motion. Although there were some similarities between the deaf and hearing native signers in terms of left hemisphere activation, only the deaf signers displayed *increased* activation of the posterior parietal cortex when processing visual motion (the hearing participants displayed the expected activation of the posterior parietal cortex). The authors suggested that this is evidence for reorganization in parietal functions following early auditory deprivation.

In a within-subjects design Rönnberg and colleagues compared PET activity for hearing adults who were early bilinguals in Swedish Sign Language (SSL) and spoken Swedish (Rönnberg, Rudner, & Ingvar, 2004). While completing tasks of working memory the bilinguals displayed parietal lobe activation when using SSL and differential activation for the right cerebellum when using the two different languages. The parietal lobe activation was similar to activation during nonverbal visuospatial tasks, and does not reflect parietal lobe activation during sign language production tasks (see also McGuire et al., 1997). This suggests that early acquisition of a visual language can lead to reorganization of areas in the parietal lobe typically used in non-linguistic visual processing. These conclusions are supported by behavioral studies of working memory in deaf signers, which have found that memory for signs relies on a phonological code similar to the phonological coding used in spoken language working memory tasks (for review see Emmorey, 2002).

Summary. Overall, studies of deaf signing individuals who rely on manual communication suggest that deafness is related to at least some aspects of nonverbal cognition—particularly processes that rely on vision. Comparisons to hearing signers suggest that the differences are likely due to deafness and not the use of a visual-manual language. In particular, it has been posited that deaf individuals have to use vision to scan for threats, in addition to using vision for communication, which may lead to differences in their generalized attention (Bavelier et al., 2006). The recent advance of cochlear implants has led to a natural comparison for the studies of deaf signing individuals just discussed. Deaf children who rely on oral-only communication also have early auditory deprivation but, unlike deaf signers, they do not have early access to language.

Deaf individuals who use oral communication and either hearing aids or cochlear implants. In addition to the studies of deaf signers, there are studies suggesting that deaf oral-only children's nonverbal development may be related to their deafness. This literature includes studies of deaf children using oral-only communication prior to the widespread use of cochlear implants, and more recent studies focused on deaf children who use cochlear implants.

In a factor analysis of deaf children's intellectual performance on the Hiskey-Nebraska Test of Learning Ability (Hiskey, 1966), Bolton found differences in memory for color and block patterns between hearing and deaf children (Bolton, 1978). The children's communication mode was not reported, but the time period of the study suggests that the children were probably using analog hearing aids and lip reading to aid their oral language development. Another study found that deaf children who used cochlear implants exhibited a delay in the development of motor sequencing and balance compared to hearing children (Schlumberger, Narbona, & Manrique, 2004). The authors also compared performance of a group of deaf children who used hearing aids, and they performed worse than both the hearing children and the deaf children who used cochlear implants. A deficit in motor sequencing ability in deaf children with cochlear implants was confirmed in another more recent study (Conway, Karpicke, et al., 2011).

Deaf oral and deaf signing children have also been found to be poorer at planning and problem solving compared to hearing children (Das & Ojile, 1995; Marschark & Everhart, 1999) although in a more recent study in which the verbal demands of the planning and problem-solving tasks were reduced, no differences were found between deaf children with cochlear implants and hearing children (Figueras, Edwards, & Langdon, 2008). Figueras and colleagues did find that deaf children with cochlear implants performed significantly worse than hearing children on other tests of executive function (e.g., card sorting). However, those differences were no longer significant once spoken language ability was factored out, suggesting that spoken language is closely tied to at least some executive function abilities in both deaf and hearing children.

Pisoni and colleagues have been investigating working memory in deaf children who use cochlear implants. They found that deaf cochlear implant users display shorter memory spans for visual sequences (Pisoni & Cleary, 2003) and that deaf children with cochlear implants had slower speaking rates and shorter digit spans compared to hearing children (Burkholder & Pisoni, 2003, 2006). A more recent study of visual sequence learning in deaf children who use cochlear implants also indicated significant group differences (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). Conway and colleagues tested 5- to 10-year-old hearing and cochlear-implanted children on a task that involved learning sequences of four colored squares. The authors found that the cochlear implant users performed significantly worse than the hearing children on the visual implicit learning task and that deaf children's performance on the task was significantly correlated with their performance on the CELF-4 (Semel et al., 2003). Another key finding was that deaf children's experience with their cochlear implant (length of implant use) was significantly correlated with their implicit learning scores, suggesting that the experience with auditory stimuli—and its corresponding sequences of speech and other auditory stimuli—increases a child's ability to learn complex visual sequences.

There are several studies demonstrating poorer visual attention in deaf children compared to hearing children (e.g., Horn, Davis, Pisoni, & Miyamoto, 2005; Khan, Edwards, & Langdon, 2005; Mitchell & Quittner, 1996; Quittner, Smith, Osberger, Mitchell, & Katz, 1994; Smith, Quittner, Osberger, & Miyamoto, 1998). Mitchell and Quittner (1996) compared the performance of deaf children aged 6- to 14-years old to a group of hearing children on tests of sustained and selective attention using the Continuous Performance Test (CPT; Gordon, 1986). Children were tested on the 'vigilance' task, in which they had to watch a stream of numbers on a computer screen and press a button each time a '1' was followed by a '9.' On that task and others, the deaf children performed more poorly than the hearing children. Similar findings were reported in Quittner et al. (1994) and Smith et al. (1998), in which visual selective attention was measured using the same visual vigilance task (CPT), which is used to measure sustained visual attention during relatively tedious tasks. These findings are consistent with the finding of Khan et al. (2005) who found that performance on the Sustained Attention subscale of the Leiter-R (Thiessen, 2011) was poorer for both deaf children with cochlear implants and for deaf children who used hearing aids, when compared to their hearing peers.

In contrast, Figueras and colleagues (Figueras et al., 2008) compared deaf children who used cochlear implants to hearing children and found no significant differences on the visual attention test of the Neuropsychological Assessment (NEPSY) (Korkman, Kirk, & Kemp, 1998). In another study, Tharpe, Ashmead, and Rothpletz (2002) used a continuous performance task similar to that used in studies by Quittner and colleagues and found no inter-group differences in visual attention when comparing deaf children with cochlear implants, deaf children with hearing aids, and hearing children, after controlling for age and nonverbal intelligence. When age was not controlled for, the deaf children with cochlear implants demonstrated significantly poorer sustained visual attention. It is important to note that the sample sizes for each of the groups in the Tharpe et al. study was small ($n = 9$ or 10) and performance was quite high in all three groups. Thus it is possible that ceiling effects on the task masked group differences in visual attention. It is also possible that the group differences found in other studies of visual attention were due to task-specific differences.

Most recently, Shafto and colleagues investigated visual habituation in a group of deaf infants prior to cochlear implantation and compared them to hearing infants (Shafto, Houston, & Bergeson, under review). In a visual habituation-oddity paradigm, they found that the deaf infants demonstrated slower habituation than the hearing infants, despite similar looking times during the first habituation trial and the presence of a novelty preference for both groups. This suggests that deafness is associated with alterations in nonverbal ability that emerge during infancy.

In addition to behavioral studies, there is evidence from neuroimaging studies that deafness affects the other sensory systems through cortical reorganization. Specifically, many researchers have found that parts of the auditory cortex get recruited for other sensory processes once a critical period of time has passed without auditory stimulation (Fine et al., 2005; Lambertz, Gizewski, de Greiff, & Forsting, 2005; Mitchell & Maslin, 2007), similar to the reorganization of the visual cortex that occurs in blind individuals. However, recent evidence suggests that individuals who receive a cochlear implant at a very young age may not experience this reorganization, instead maintaining typical auditory and visual cortical regions (Dorman, Sharma, Gilley, Martin, & Roland, 2007; Gilley, Sharma, & Dorman, 2008; Sharma, Gilley, Dorman, & Baldwin, 2007). This could lead to modality–specific differences in brain activity, and consequently, different patterns of behavior in deaf individuals who use sign language compared to deaf individuals with cochlear implants who use spoken language.

Potential mechanisms for the relation between deafness and nonverbal ability. There are at least two possible explanations for why deafness relates to general cognitive abilities. One is that language and other cognitive skills develop interdependently and because deaf children's spoken language skills develop at a later age than is typical, their general cognitive skills (e.g., visual habituation) are also delayed. This hypothesis is supported by results from a study of 8- to 12-year-old deaf children (Figueras et al., 2008). Figueras et al. argued that a correlation between spoken language ability and executive function is evidence that these abilities are coupled across development.

A second explanation is the atypical cognitive ability of deaf children is due to early auditory deprivation. Quittner et al.(1994) found that deaf children who received cochlear implants showed faster improvement of their visual attention skills over the course of a year relative to deaf children who continued to use conventional hearing aids. They and others (Dye & Bavelier, 2010; Smith et al., 1998) have argued that due to early auditory deprivation, deaf infants and children must learn to distribute and control their focus of attention more broadly than hearing children (in order to act as an alerting sense) and that this leads to fundamental differences in how they allocate visual attention (i.e., they allocate more attention to the periphery than to the central visual field). The auditory deprivation theory is also consistent with results from studies of deaf adult signers (who have experienced auditory, but not language deprivation) who demonstrate different visual peripheral skills compared to both hearing adults with no sign language experience and hearing adults who are native signers (see Bavelier et al., 2006 for review).

Summary. There is growing evidence that deafness is related to at least some general cognitive processes both in deaf individuals who use sign language and in deaf individuals who only use oral language to communicate. Notably, there are no published studies on the nonverbal abilities of deaf *infants* so we do not know when and why differences in general cognitive ability emerge. We also do not know how or whether these differences in general cognitive ability relate to spoken language development in deaf children. It may be that deafness is related to general cognitive abilities, which then is related to spoken language development via domain-general processes. Alternatively, deafness could be related to spoken language development via modality- and domain-specific processes. What is known about the relationship between general cognitive abilities and spoken language development in both hearing and deaf children is discussed in the next section.

The Relation between Nonverbal Cognition and Spoken Language Development

One aspect of this dissertation addresses the potential link between nonverbal cognitive performance in infancy and spoken language outcomes. Although one recent study found no correlation between nonverbal cognitive abilities and some verbal tasks with the hearing children in their study (Newman et al., 2006), many other studies have found a strong link between nonverbal and verbal cognitive abilities (e.g., Plomin & Dale, 2000).

In typical development. Verbal abilities have been found to correlate with both nonverbal cognitive and nonverbal motor skills. For example, motor control and coordination have been found to be strongly associated with pre-verbal vocalizations in infants (Ejiri & Masataka, 2001; Iverson & Fagan, 2004) and language-based measures in adults (Carello, LeVasseur, & Schmidt, 2002). This dissertation focuses specifically on nonverbal *cognitive* abilities. The cognitive abilities most widely studied with regard to language outcomes are visual recognition memory, habituation, and visual attention. Each is discussed in turn.

One cognitive process that has been found to be highly related to outcomes is visual recognition memory (e.g., Colombo et al., 2004; Fagan & McGrath, 1981). Visual recognition memory is the process of recognizing a previously-familiarized stimulus and distinguishing it from a stimulus that is novel. Recognition memory requires learning to attend to some features (e.g., shape) while ignoring others (e.g., color) in order to form perceptual categories. Rose and colleagues have found that better information processing is correlated with better visual recognition memory and consequently better cognitive outcomes (Rose & Feldman, 1997; Rose, Feldman, & Jankowski, 2001). Rose has argued that children's abstraction of perceptual features forms the basis for concepts of objects and that these concepts need to be in place before language may be acquired (Rose et al., 1991). Rose has also investigated specific language outcomes that correlate with recognition memory, and has found positive correlations with receptive and expressive language at 2.5, 3, 4, and 6 years old, vocabulary ability at 4, 7, and 11 years old, IQ at 3, 4, 5, 6, and 11 years old, and language proficiency at 3 years of age (Rose, Feldman, & Jankowski, 2004; Rose et al., 1991). More recently the same researchers conducted research suggesting that aspects of memory and representational competence (the ability to extract commonalties from experiences and represent them abstractly or symbolically) are also related to language outcomes at 12 and 36 months (Rose et al., 2009) and to executive functions at 11 years of age (Rose et al., 2012).

Attention abilities and habituation processes are also thought to be important for development (e.g., Colombo et al., 2004; Fagan, 1984b; D. J. Miller, Spiridigliozzi, Ryan, Callan, & McLaughlin, 1980; Rose & Feldman, 1997; Sigman, Cohen, & Beckwith, 1997). Some of the first researchers to systematically investigate a relationship between habituation and cognitive outcomes found habituation performance in infancy to account for up to 30 percent of the variance in cognitive ability in the preschool years (Bornstein & Ruddy, 1984; Lewis, Goldberg, & Campbell, 1969; D. J. Miller et al., 1979; D. J. Miller et al., 1977; D. J. Miller, Sinnott, Short, & Hains, 1976; D. J. Miller et al., 1980; Ruddy & Bornstein, 1982). Later studies have continued to find at least moderate relations between habituation behavior and novelty preferences in infancy and performance on cognitive tasks at later ages (Bornstein & Sigman, 1986; Colombo, 1993).

Since the 1980s and 1990s many other researchers have investigated the relation between habituation and visual attention in infancy and outcome measures of various kinds. For example, Colombo et al. (2009) found visual habituation during infancy to correlate with vocabulary ability at later ages. This has led him and others to suggest that attention is a basic component of cognition and that it plays an important role in language development. Taken together, these findings suggest that individual differences in some aspects of visual attention during infancy are relatively stable and are related to the development of other cognitive skills. Findings like these have also informed theories of the processes that underlie cognitive functioning, such as focused attention, speed of processing, inhibition, and memory (Colombo & Frick, 1999; Colombo & Mitchell, 1990; Fagan, 1984b; Rose & Feldman, 1997).

In deaf children. While the research discussed thus far was all conducted with hearing children, a correlation between nonverbal and verbal abilities is also supported by research with deaf children. Published studies of deaf children with cochlear implants include investigations of sequencing abilities, executive function, visual attention, and working memory. In addition, language impairments, such as specific language impairment (SLI), are associated with impaired cognitive processing (Benasich & Tallal, 2002) and impaired auditory processing (Choudbury, Leppänen, Leevers, & Benasich, 2007).

Conway and colleagues (Conway, Karpicke, et al., 2011) recently found that performance on a motor sequencing task was correlated with performance on the CELF-4 (Semel et al., 2003) for deaf children who use cochlear implants. This is similar to the finding from the same research group that performance on a visual (nonverbal) sequence learning task was correlated with performance on the CELF-4 for deaf children who use cochlear implants (Conway, Pisoni, et al., 2011). The authors posited that sequential learning is related to language development because both are laden with sequential and temporal information.

A study by Figueras et al. (2008) found that deaf children with cochlear implants performed similarly to hearing children on tests of executive function (e.g., card sorting) once spoken language ability was factored out. This suggests that spoken language is closely tied to at least some executive function abilities in both deaf and hearing children. There is also evidence of a relation between language development and sustained visual attention. Horn et al. (2005) found that for deaf children who used cochlear implants, their performance on the CPT (Gordon, 1986) correlated with their receptive language scores on the Reynell Developmental Language Scales (Reynell & Huntley, 1985). In addition, Cleary and colleagues found a relation between working memory and spoken word recognition and vocabulary in deaf children who use cochlear implants (Cleary, Pisoni, & Kirk, 2000).

Summary. Taken together, these findings illustrate the importance of understanding the role of nonverbal cognitive abilities in a context where verbal abilities are being acquired at a later age (as is the case for deaf children who use cochlear implants). More research is needed to determine the specific relation between nonverbal cognitive ability and language outcomes in young deaf cochlear implant users, which is important for understanding the mechanisms that underlie spoken language development. One possibility is that general cognitive abilities influence language development. Another is that language ability influences general cognitive abilities. It could also be that some other factor (or factors) influences the development of both general cognitive and language abilities. Whatever the case, in order to try to tease apart language and general cognitive development, we need to examine these abilities during infancy. That is one of the objectives of this dissertation.

Specific Research Questions

The current dissertation addresses 5 specific research questions using the Visual Sequence Learning (VSL) and Visual Recognition Memory (VRM) tasks, which are described in detail in Chapter II. Each research question is listed below, along with a description of how it is addressed. Each research question is addressed by a study (or collection of studies), which is written in manuscript format in a separate chapter – Chapters III–VI. Research question 1 investigates the effect of deafness on nonverbal cognitive skills during infancy. Research questions 2 and 3 address the potential link between nonverbal cognitive performance in infancy and spoken language outcomes for infants with normal hearing ability. Research questions 4 and 5 address the potential link between nonverbal cognitive ability in infancy and spoken language outcomes for deaf infants who use cochlear implants.

1. Is early deafness related to nonverbal cognitive abilities in deaf infants? Specifically, do children who have experienced early auditory and language deprivation (as deaf infants prior to cochlear implantation) have deficits in implicit visual sequence learning or visual recognition memory? (Chapter III)

In order to test whether deafness is related to nonverbal cognitive processes, deaf infants were tested on two nonverbal cognitive tasks: the VSL and the VRM. Their performance was compared to hearing infants who were approximately the same chronological age. If there are significant differences between the hearing age-matched and the deaf infants, meaning that the deaf infants have slower reaction times or are unable to learn the visual sequence in VSL and unable to recognize familiarized images in VRM, that would suggest that deafness is negatively related to general cognitive processes, or at least the two processes tested with these experimental tasks. This pattern of results would be consistent with recent research suggesting general cognitive differences in deaf and hearing infants (Shafto et al., under review). Such a pattern, in which group differences cross modality, would also suggest that modality-general processes underlie sequence learning and recognition memory.

If the deaf and hearing infants perform similarly on the two experimental tasks, this would suggest that deafness may not be related to visual sequence learning and visual recognition memory as assessed through the VSL and VRM tasks. This would suggest that sequence learning and recognition memory are modality specific, such that auditory deprivation does not affect (visual) task performance. It is also possible that deaf infants would show a different pattern of performance compared to the hearing infants on only one of the two experimental tasks. That pattern of results would suggest that deafness is only related to some general cognitive processes.

2. Does sequence learning, as a domain-general process, relate to spoken language development in a group of infants with typical hearing ability? (Chapter IV)

Chapter IV presents an investigation of the relation between early language development and performance on the VSL task as a test of domain-generality in language acquisition. Infants' performance on the VSL task was correlated with reported CDI vocabulary and grammatical measures at later ages (up to 30 months old) for a group of hearing infants, aged approximately 8.5 months old. One possibility is that there would be a positive correlation between the ability to learn a spatiotemporal sequence (performance on the VSL task) and early grammatical ability (e.g., the consistent use of regular inflectional morphology; for example, adding '-ed' for past tense). It is also possible that performance on the VSL could be correlated with CDI vocabulary. These patterns of results would suggest that the domain-general process of sequence learning is related to spoken language development. A pattern of results in which performance on the VSL task does not correlate with either CDI vocabulary or grammatical ability would suggest that either there is not a relationship between visual sequential learning and vocabulary/grammatical ability, or that there is not a longitudinally predictive relation. Finally, it is possible that the VSL task could be significantly correlated with both CDI vocabulary and grammatical ability, but that it accounts for different amounts of the variability in vocabulary compared to grammar. The interpretation of this particular pattern of results would depend on the strength of the correlations.

3. Is visual recognition memory a significant correlate of early language development in a group of infants with typical hearing ability? (Chapter V)

Chapter V presents an investigation of the relation between early language development and performance on the VRM task as a test of domain-generality in language acquisition. Infants' performance on the VRM task was correlated with reported CDI vocabulary and grammatical measures at later ages (up to 30 months old) for a group of hearing infants, aged approximately 8.5 months old. The expectation was that this would replicate previous research by finding a positive correlation between visual recognition memory at approximately 8.5 months old and English receptive vocabulary (Rose & Feldman, 1995) and expressive language (Rose et al., 1991) as a toddler. A pattern of results in which performance on the VRM task does not relate to CDI vocabulary would suggest that our VRM task was not ideally set up (i.e., does not measure recognition memory in the same manner as previous studies by Rose and colleagues).

4. Does performance on a visual sequence learning task relate to spoken language ability in deaf infants who use cochlear implants? (Chapter VI)

The fourth research question aimed to determine the relation between nonverbal cognitive ability during infancy (VSL task performance) and spoken language ability after a period of cochlear implant use in deaf infants. The deaf infants' performance on the VSL task was tested as a predictor of their reported vocabulary abilities in a growth curve analysis. Significant relations between performance on the VSL task and the language measures would suggest similarities in the cognitive underpinnings of language with hearing children (e.g., Plomin & Dale, 2000). Nonsignificant correlations between VSL performance and the language measures would suggest that the nonverbal cognitive ability tapped in this task is not critical for spoken language development in deaf children who use cochlear implants. This pattern of results would suggest that potential deficits in nonverbal cognitive ability are not necessarily associated with poorer spoken language ability in deaf children who use cochlear implants.

5. Does performance on a visual recognition memory task relate to spoken language ability in deaf infants who use cochlear implants? (Chapter VI)

The fifth research question, in conjunction with research question 4, aimed to determine the relation between nonverbal cognitive ability during infancy (in this case, VRM task performance) and spoken language ability after a period of cochlear implant use in deaf infants. The deaf infants' performance on the VRM task was tested as a predictor of their reported vocabulary abilities in a growth curve analysis. Significant relations between performance on the VRM task and the language measures would suggest similarities in the cognitive underpinnings of language with hearing children (e.g., Plomin & Dale, 2000). Nonsignificant correlations between VRM performance and the language measures would suggest that visual recognition memory is not critical for spoken language development in deaf children who use cochlear implants. This pattern of results would suggest that potential deficits in nonverbal cognitive ability are not necessarily associated with poorer spoken language ability in deaf children who use cochlear implants.

CHAPTER II

METHODOLOGY

Novelty Versus Familiarity Preference

For more than 50 years developmental researchers have been relying on infant nonverbal behavioral responses to indicate underlying ability. The novelty effect is one measure that has been used for infants of a wide range of ages. In order to elicit a novelty effect, an infant is typically exposed (familiarized) to one stimulus for some amount of time and then exposed to a second *novel* stimulus. The novelty *effect* occurs when the infant attends to (looks at) the novel stimulus longer than to the familiarized stimulus. This may sound like a straightforward behavioral method, but decades of research have demonstrated that measuring the novelty effect in infants can be quite difficult (see e.g., Hunter & Ames, 1988 for review). First of all, within an age range different amounts of familiarization time can lead to either a familiarity (preference for the familiar stimulus) or a novelty (preference for the novel stimulus) effect. Infants of different ages also require different amounts of familiarization time (which is monotonic with age) in order to elicit a novelty effect. That means that the same amount of familiarization for infants of one age might yield a novelty effect, while for infants of a different age the same familiarization time might yield a familiarity effect. In addition, the familiarization time required to elicit a novelty effect can also vary depending on the complexity of the stimulus, such that more complex stimuli or tasks would require longer amounts of time for information processing (see Cohen, Deloache, & Rissman, 1975; Hunter, Ames, & Koopman, 1983; Ross, 1974).

In the current dissertation, the Visual Recognition Memory (VRM) task was designed with the expectation that the 8.5-month-old infants would display a novelty effect. Specifically, the familiarization time was set to 10 seconds, which, according to Rose and colleagues (see Rose et al., 2001), is the appropriate familiarization time needed in order for normal-hearing infants aged 5- or 7-months-old to demonstrate a novelty effect. Slightly older infants (~8.5 months) were tested so that they would be the same age as the VSL task, and so that we could use the CDI. Because this task has not been used with normal-hearing infants as old as 23 months, there was no clear precedent for the appropriate amount of familiarization time to use with the deaf infants. The youngest of the deaf infants was ~8 months old, so the same familiarization time (10 seconds) was used for all of the deaf infants on the VRM.

Experimental Measures

This study was approved by the Institutional Review Boards of the University of Louisville (IRB #09.0218) and Indiana University (IRB #0010-01B). All applicable research adheres to basic ethical considerations for the protection of human participants in research and informed parental consent was obtained after the nature and possible consequences of the study were explained. The two experimental tasks used in this dissertation were meant to tap distinct cognitive abilities. In particular, the visual sequence learning (VSL) task was designed to tap procedural learning, while the visual recognition memory (VRM) task was designed to tap declarative memory.

Visual Sequence Learning Task

A novel VSL task was used, which relies on reaction time to assess how well infants learned a simple repeating 3-item spatiotemporal sequence. The task is similar to paradigms used by Haith and colleagues (e.g., Wentworth & Haith, 1998; Wentworth, Haith, & Hood, 2002), McMurray (e.g., McMurray & Aslin, 2004), and Kirkham (Kirkham et al., 2007), but was modeled more directly after the paradigm in Clohessy, Posner, and Rothbart (2001). A 3-item temporal sequence was used (rather than the 2-item sequences that have been used in most infant studies that relied on reaction time) because it is more complex than a 2-item sequence, and, thus more likely to tap those cognitive processes of interest (e.g., language acquisition, which involves complex sequences).

Because this is a novel task, and previous studies have not used a visual-only task, there is no evidence of reliability or validity on the task in either infants with normal hearing or deaf infants of any age. In order to ensure some reliability of the task, before running this task on deaf infants, it was first tested on over 50 infants with normal hearing aged 8-9 months old. Then, once testing began with deaf infants on the task, infants with normal hearing who were matched on age to the deaf infants were also recruited. Testing both deaf and normal-hearing infants of the same chronological age should allow us to tease out results that are a result of the task being age-inappropriate, from results due to inappropriateness of the task for deaf infants.

The VSL task assesses infants' ability to learn a sequence of spatial locations. The prediction is that as infants learn the sequence they would get faster at orienting to the next stimulus location in the sequence. At the time of participation, a receptive language measure, the MacArthur-Bates Communicative Development Inventory (Fenson et al., 2006), was used to probe the relation between VSL performance and language comprehension ability, which is developing well before infants begin to speak. Finally, additional language measures were collected at a later time point—at approximately 13.5 months old—to investigate the predictive relation between VSL and language comprehension several months after participating in the study.

Apparatus. The VSL task was conducted within a custom-built double-walled IAC sound booth approximately 6 feet in width. Infants were tested while seated on a caregiver's lap in front of a 55-inch HDTV monitor with two 19-inch Dell computer monitors on either sidewall (see Figure 2-1). Infants sat on the caregiver's lap so that the monitors were approximately eye level; the side monitors were at an angle of 57 degrees. Experimental sessions were recorded via a hidden camera and the experimenter (unable to see which stimulus was being presented) observed the session on a monitor that displayed the live-action video of the infant and controlled the stimulus presentation from outside the sound booth. For children tested at the Infant Speech Lab the experiment was controlled by the Habit software package (Cohen, Atkinson, & Chaput, 2004) run on a Macintosh G4 desktop computer. For children tested at the Heuser Hearing Institute, the experiment was controlled by a program written with MATLAB software (The Mathworks, 2008) run on a Windows-based desktop PC. The booth was darkened during testing to reduce visual distractions.

Stimuli. Although the task was modeled after Clohessy, Posner, and Rothbart (2001) the images were not paired with sounds. The current version is only visual so that it can be used with deaf infants in addition to infants with normal hearing. The stimuli consisted of twelve 2D visual images of colorful geometric shapes organized into four object sets (A-D; see Figure 2-2). Each object set consisted of three unique geometric shapes created using the Adobe custom shape tool in Adobe Photoshop CS3 (Knoll et al., 2007). The use of four different object sets was to hold the infants' attention during the task. The Photoshop .png files were then animated using Final Cut Express HD so that they appeared to loom in and out. The shapes were made to loom instead of being static images based on a previous finding that infants' attention was not sufficiently maintained when using static images (Kirkham et al., 2002). The looming images were saved as Quicktime movies. The items in each set were all different colors and shapes, selected such that no color or shape repeated within or between sequences. All stimuli loomed from small to large and back to small within 2.66 seconds, and each stimulus loomed up to five times within the course of one trial or presentation. The maximum size for each shape was either 31 cm or 34 cm depending upon whether the shape appeared on the center or side monitors, respectively. Again, the side monitors were each at an angle of 57 degrees. No infant saw the same shape on both the side and center monitors so this slight difference in size and visual angle is not likely to have had any bearing on infants' performance on the task.

Procedure. The experiment consisted of one pre-test phase, one learning phase (Phase 1), and one test phase (Phase 2). In each phase, the stimulus presentation was contingent upon the infant looking at the monitor (infant controlled). Each trial (an individual stimulus presentation) began with the appearance of a stimulus and ended 700 milliseconds after the infant looked at the correct stimulus location. Stimuli within each sequence were separated by an inter-stimulus interval of 1100 milliseconds. An entire 3-

item sequence thus consisted of 3 trials in 3 different spatial locations (either Left-Center-Right or Right-Center-Left). The experimental session consisted of 3 pre-test trials (1 sequence presentation), 12 learning trials (4 sequences; Phase 1), and another 12 test trials (4 sequences; Phase 2). The entire session lasted for a maximum of 7 minutes with each phase lasting a maximum of 3.6 minutes. The actual length of the sequences and phases varied dependent on how quickly the infant looked at the monitor, with an average testing session of 3 to 4 minutes.

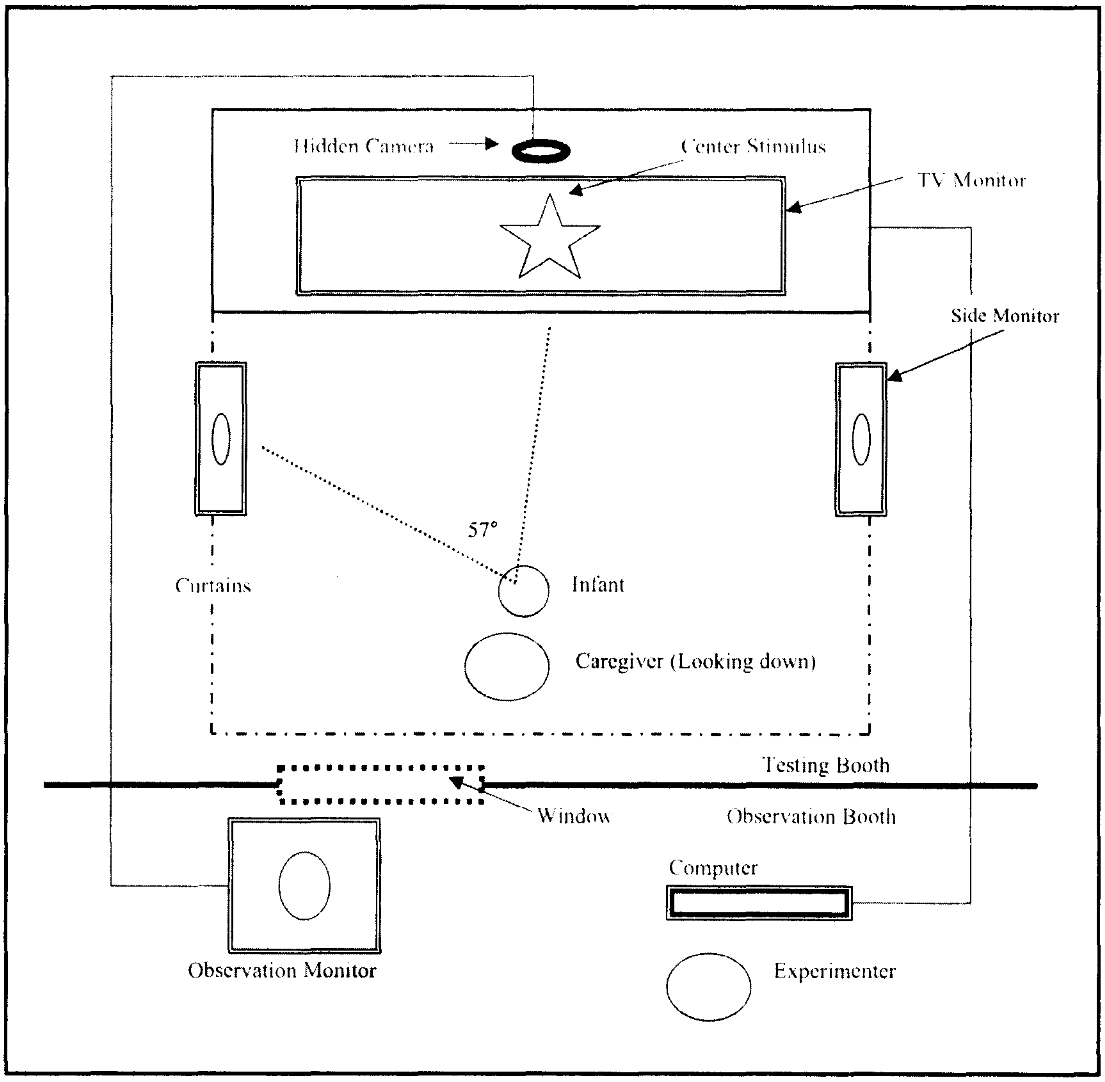

Figure 2-1. Sound Booth set-up for the Visual Sequence Learning task.

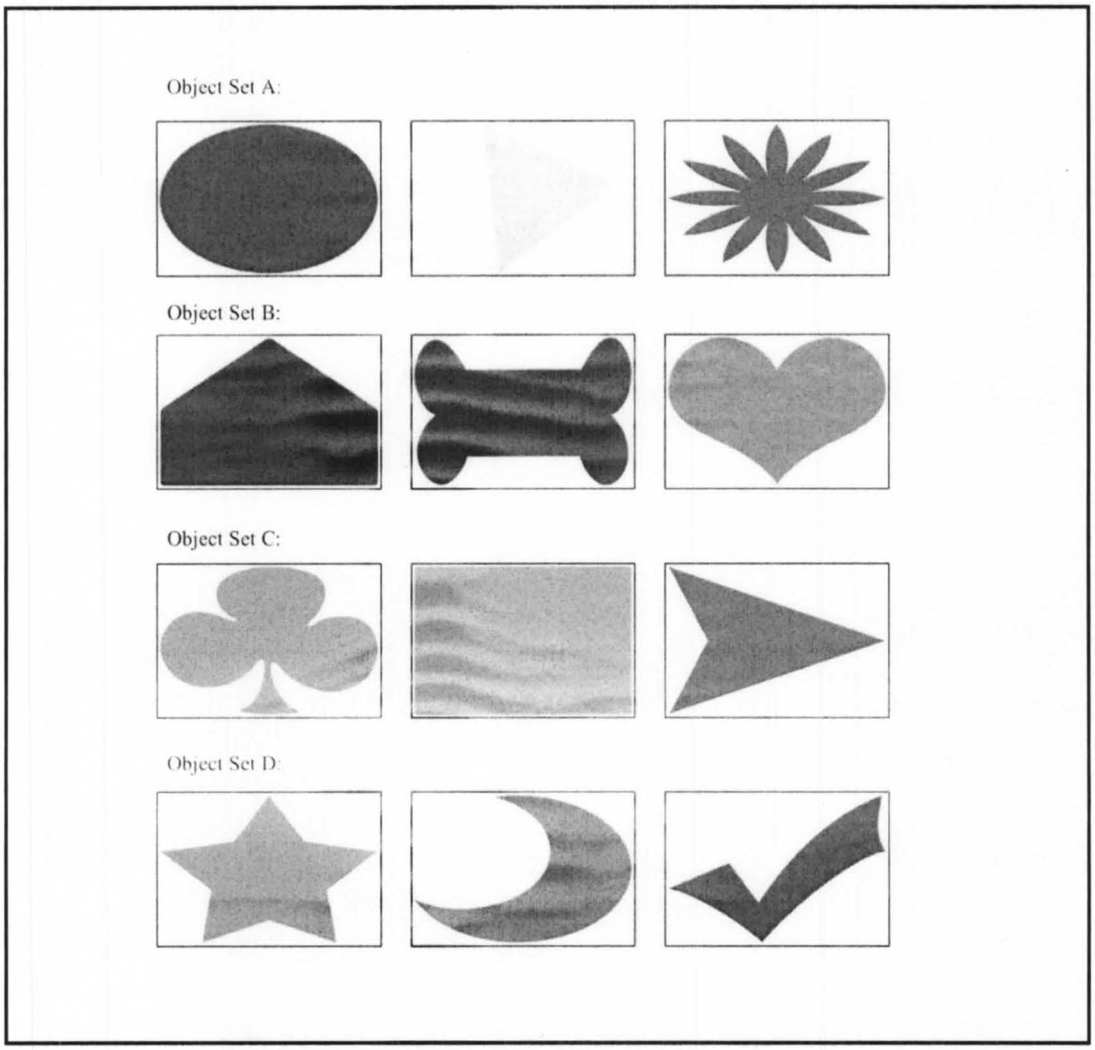

Figure 2-2. Stimuli sets for the Visual Sequence Learning task.

Each phase was presented to the infant without breaks or pauses. The parent or caregiver holding the infant was instructed to look down and keep their eyes closed to limit their influence on the infant's direction of eye gaze at the monitors. Infants' eye movements (sometimes relying on head movements) were analyzed offline to determine how quickly infants reacted to the correct location of the next stimulus.

Pre-test phase. To orient the infant to the task, warm-up stimuli were displayed in a particular spatiotemporal sequence. A looming blue lightning bolt on a white background was presented on each monitor, in one of two sequence orders (randomly assigned): Center, Left, Right (C-L-R) or Right, Left, Center (R-L-C). Two different Pre-test sequences were used to prevent the last trial of the Pre-test phase from appearing on the same monitor as the first trial of Phase 1 (see below). Infants were presented with a total of three pre-test trials. (i.e., 1 sequence presentation). The Pre-test was not used for inclusion/exclusion purposes, but rather to familiarize the infants with the task prior to learning the test sequence.

Phase 1: Learning phase. In Phase 1, infants were presented with one of the object sets (A-D; randomly assigned) in one of two spatiotemporal patterns (L-C-R or R-C-L) that repeated continuously (e.g., L-C-R / L-C-R / L-C-R, etc.). If the infant saw C-L-R in the pre-test phase, then the spatiotemporal sequence for Phase 1 was L-C-R. If the infant saw R-L-C during the Pre-test phase, then the spatiotemporal sequence that followed was R-C-L. Shapes within each object set were always presented in the same location, even when the spatial pattern was different. For example, if one infant observed Object Set A in the L-C-R pattern and another observed Object Set A in the R-C-L pattern, both infants saw an ellipse on the left monitor, a triangle on the center, and a flower on the right; all that was different between infants was the temporal order in which these images appeared (L-C-R or R-C-L).

Phase 2: Test phase. In Phase 2, the infant was tested for his/her ability to predict the location of the next stimulus based upon the spatial pattern seen in Phase 1. A new set of objects was used but they were presented in the same spatiotemporal sequence as Phase 1.

Data collection. The video recordings of the experimental sessions were recorded at 29.97 frames per second and were coded offline using Supercoder (Hollich, 2005) for right, left, and center looks. The only eye movements coded were incorrect anticipatory looks and correct looks (either anticipatory or reactionary). Thus there were no more than 2 eye movements coded per trial. Because each look was to indicate RT, an eye movement was coded as the first look *toward* the stimulus. A first coder coded eye movements for all of the trials for all of the infants. Then for each participant group a second coder (who was blind to the purpose of the experiment) coded all trials for a randomly-selected 25 percent of the infants for reliability. Reliability coding information for the 8.5-month-old normal-hearing infants is reported in Chapter IV. The coded files were then run through an Excel Macros program, which calculated the RTs for each trial. The RT for trial X was the time between the onset of trial X and the onset of the first correct look toward the correct location for trial X. Thus some RTs were negative (if they were anticipatory).

An anticipatory look was a look to the correct location that occurred before or during the first 150 ms after the onset of the current stimulus (see Johnson, Amso, & Slemmer, 2003). Thus, a look was counted as anticipatory even if it ended before the onset of the stimulus. Anticipatory looks were classified as correct or incorrect dependent on whether the infant looked to the correct location of the next stimulus.

In order to test for learning of the sequence, the median RT for each phase was used as the RT for that phase. Therefore each infant had 2 data points: the median RT for Phase 1 and the median RT for Phase 2. Medians were used rather than means in order to remove the influence of outlier trials, as was done in previous research on anticipations and RT in infants (Haith & McCarty, 1990). The proportion of change in median RTs between the two phases—Phase 1 RT minus Phase 2 RT (hereafter the 'RT difference score')—was then calculated and formed the basis for analyses. Prior to deciding on this dependent variable calculation, preliminary analyses were conducted using different metrics for the RT measure. For example, analyses were run using the mean RT, and using an RT measure that accounted for the distance between stimuli locations (i.e., that a look from right to left takes longer than a look from right to center). These different metrics did not yield a different pattern of results.

An additional dependent variable was calculated as the increase in the number of correct anticipatory looks from Phase 1 to 2. Thus there were two dependent variables for analysis: the RT difference score and the change in correct anticipatory looks from Phase 1 to 2. A decrease in RT from Phase 1 to Phase 2—a speeding up of the reaction—or an increase in the number of correct anticipatory looks was taken as indicating learning of the sequence.

Visual Recognition Memory Task

The Visual Recognition Memory task (VRM) was modeled after a task designed by Rose et al (2001). It employs a span–task paired–comparison paradigm that requires attending to some features while ignoring others in order to form perceptual categories. This task has been used by Rose and colleagues for over 10 years on infants aged 5 to 12 months old, including both pre-term and full-term infants. They have found the task to reliably elicit a novelty preference, which they have taken to be an index of infants' information processing and memory for visual objects. To our knowledge, this task has not been used with infants over the age of 12 months, or infants of any age who have hearing impairment. Over 50 infants with normal hearing aged 8-9 months old were tested first in order to validate the set-up. Then testing began with deaf infants, and infants with normal hearing (who were matched on chronological age to the deaf infants) were also recruited. As with the VSL task, testing both deaf and normal-hearing infants of the same chronological age should allow us to tease out results that are a result of the task being age-inappropriate, from results due to inappropriateness of the task for deaf infants.

In the current version of this task, a series of images was shown for familiarization, followed by the same images paired with new images for the test phase. The target images were in either a series of two or three (spans) and the percentage of time looking at the new image was calculated (see Rose et al., 2001). This preference for looking at the new image is taken to indicate short term memory, or visual recognition memory.

Apparatus. The Apparatus was the same as for the VSL task (see Figure 2-3 for a schematic of the testing sound booth).

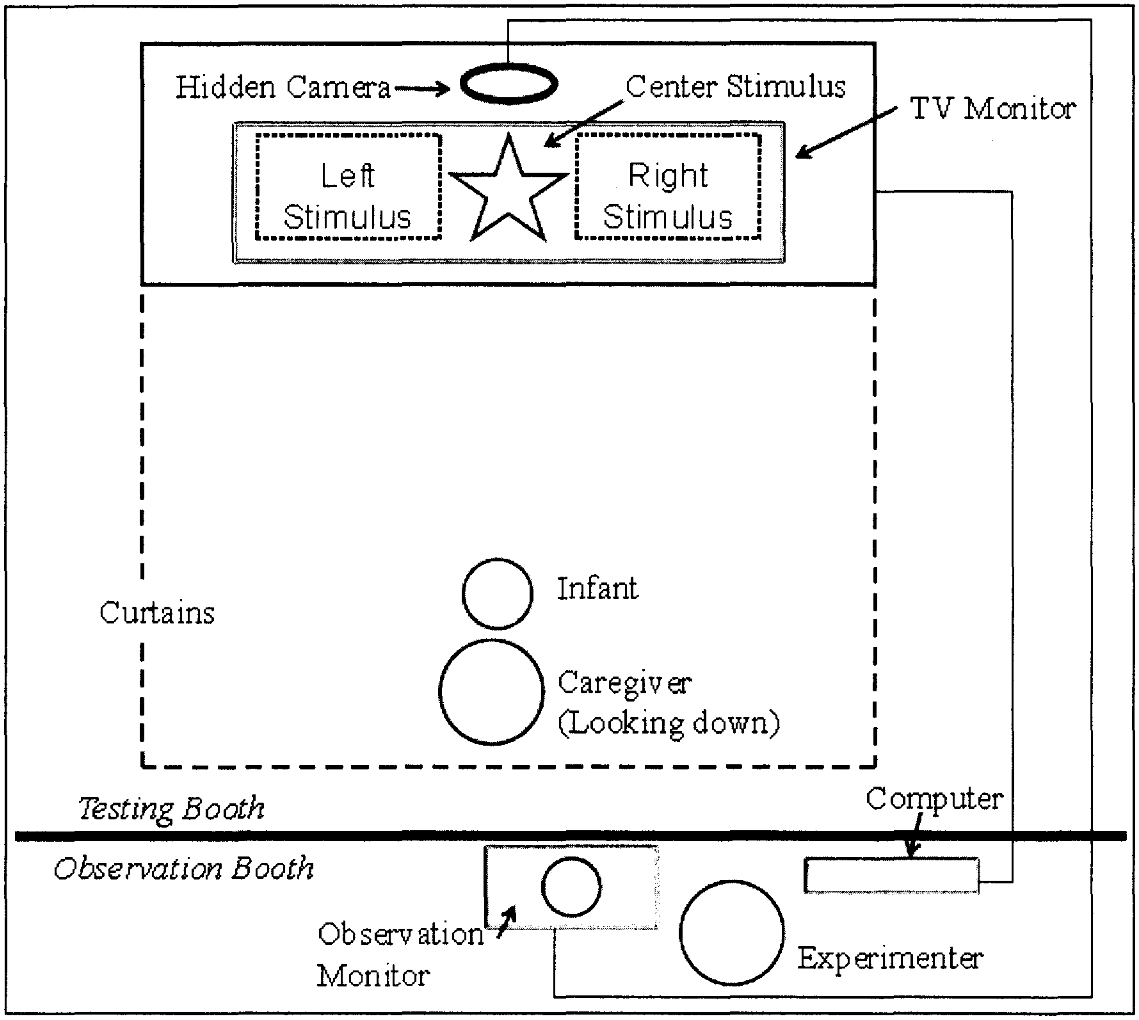

Figure 2-3. Sound Booth set-up for the Visual Recognition Memory task.

Stimuli. The stimuli consisted of 14 images of colorful objects. Images were found using an image search on the Internet and were selected if it was unlikely that the infant would already be familiar with the image (e.g., an image of a spoon was not selected since it is likely that the infant has seen a spoon before, but an image of a unique candleholder would have been selected). Images were then organized into 7 pairs: 2 pairs for familiarizing the infant to the testing procedure (the Pre-test Phase) and 5 pairs for the experiment (the Test Phases). Image pairs were designed to be easily discriminable from each other, yet equal in attractiveness (see Figure 2-4).

In order to create the paired–image slides, Photoshop (Knoll et al., 2007) was used to create an initial 12x8 inch blue background template slide with two equally–sized white boxes placed side by side on top of the blue background. Next, the individual images from each pair were made an equal size (0.75 x 0.75 inches) and pasted within the white boxes. This process was repeated for each paired set of images to yield a collection of test slides (7 total) that were identical to one another except for the image in each white box. Two additional familiarization slides were then made for each corresponding paired–image slide. These familiarization slides consisted of the same 12x8 inch blue background slide with a single centrally–located white box, which was equivalent in size to the paired–image slide boxes and which contained one of the images. Each familiarization slide corresponding to a given paired–image slide consisted of one of the two images in the pair. For example, if a paired–image slide consisted of images A and A' (the prime denoting the novel image), two familiarization slides were created—one with image A in the centrally–located box, and the other with image A' in the centrally–located box. This was done for counterbalancing purposes so that any bias for one image over the other would be canceled out as half of the infants were familiarized with image A and the other half with A'. This process was repeated for every paired–image slide of the Test Phases and for only one of the two images in each of the two Pre-test Phase slides, thus yielding a total of 12 familiarization slides (10 for the Test Phases and 2 for the Pre-test Phase).

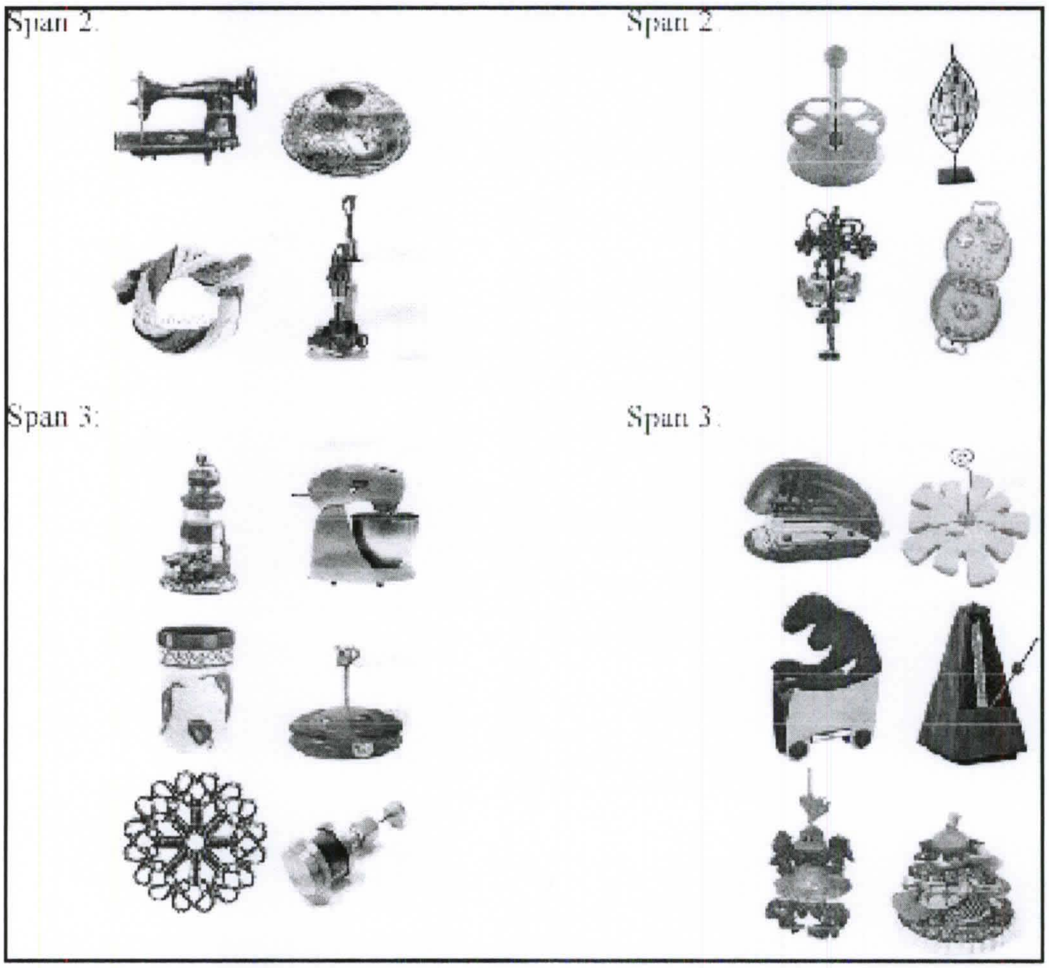

Figure 2-4. Stimuli sets for the Visual Recognition Memory task.

Once pairs were created, pairs were further organized into two sets of spans consisting of either two or three objects. Extra care was taken to ensure that images that appeared in the left boxes of the Test slides were all quite different from one another, and images that appeared in the right boxes were quite different from one another.

Aside from the 14 stimuli, an "attention-getter" video clip was also created. This clip consisted of a black screen with an animation of a baby laughing in the center of the screen. This was used to redirect the infants' attention to the screen between trials.

Procedure. The basic design of the experiment consisted of 3 phases—a Pre-test followed by 2 Test Phases. There were two Test Phases: one of span length 2 and one of span length 3. The procedure for each phase followed a paired–comparison paradigm. The infant was first familiarized to two or three images in succession (depending on span length), and then given a series of test trials with each successive familiar image now paired with a new image. For example, for a phase with a span of two images, the infant was first familiarized to images A and B in succession, and then shown A vs. A' and B vs. B' as tests of recognition memory (see Figure 2-5). Note that previous studies have demonstrated that ascending versus descending order of span length does not affect the outcome of results (Rose et al., 2001).

Pre-Test phase. Two initial Pre-test trials of span length 1 were presented first to familiarize infants with the testing procedure. Each Pre-test trial consisted of a single familiarization slide (i.e., image A) followed by its corresponding paired–image slide (i.e., A vs. A'), with the novel image on the right side for Pre-test test trial 1 and on the left side for Pre-test test trial 2. Each familiarization and test slide was shown for a total of 10 seconds and between slides the brief "attention-getter" clip was shown to redirect the infant's attention to the screen.

Test phases. For the Test phases of the experiment, infants were presented with a span-2 phase and a span-3 phase. Within each Test phase the familiarization slides were shown for a total of 10 seconds, followed immediately by the paired–image slides, which were shown for 5 seconds. Familiarization slides were selected to ensure that there were an equal number of paired–image slides with the novel stimulus on the right and left sides to control for side preference. Between each slide, the infant's attention was redirected to the screen using the "attention-getter" clip.

Data collection. The video recordings of the experimental sessions were recorded at 29.97 frames per second and were coded offline using Supercoder (Hollich, 2005). The only eye movements coded were looks to the on-screen stimulus—looks to the center for familiarization slides, and looks to the left/right for test slides. The beginning of the look was coded as the first frame where the child's eyes were focused on the stimulus, and the end of the look was the last frame where the child's eyes were focused on the stimulus before looking away. On a given trial a child could have multiple looks. For example, s/he could look from the stimulus to something off-screen and back, or s/he could look back and forth between the left and right stimuli on a test slide.

A first coder coded eye movements for all of the test trials for all of the infants. Then for each participant group a second coder (who was blind to the purpose of the experiment) coded all trials for a randomly-selected 25 percent of the infants for reliability. Reliability coding information for the deaf infants and their age-matched

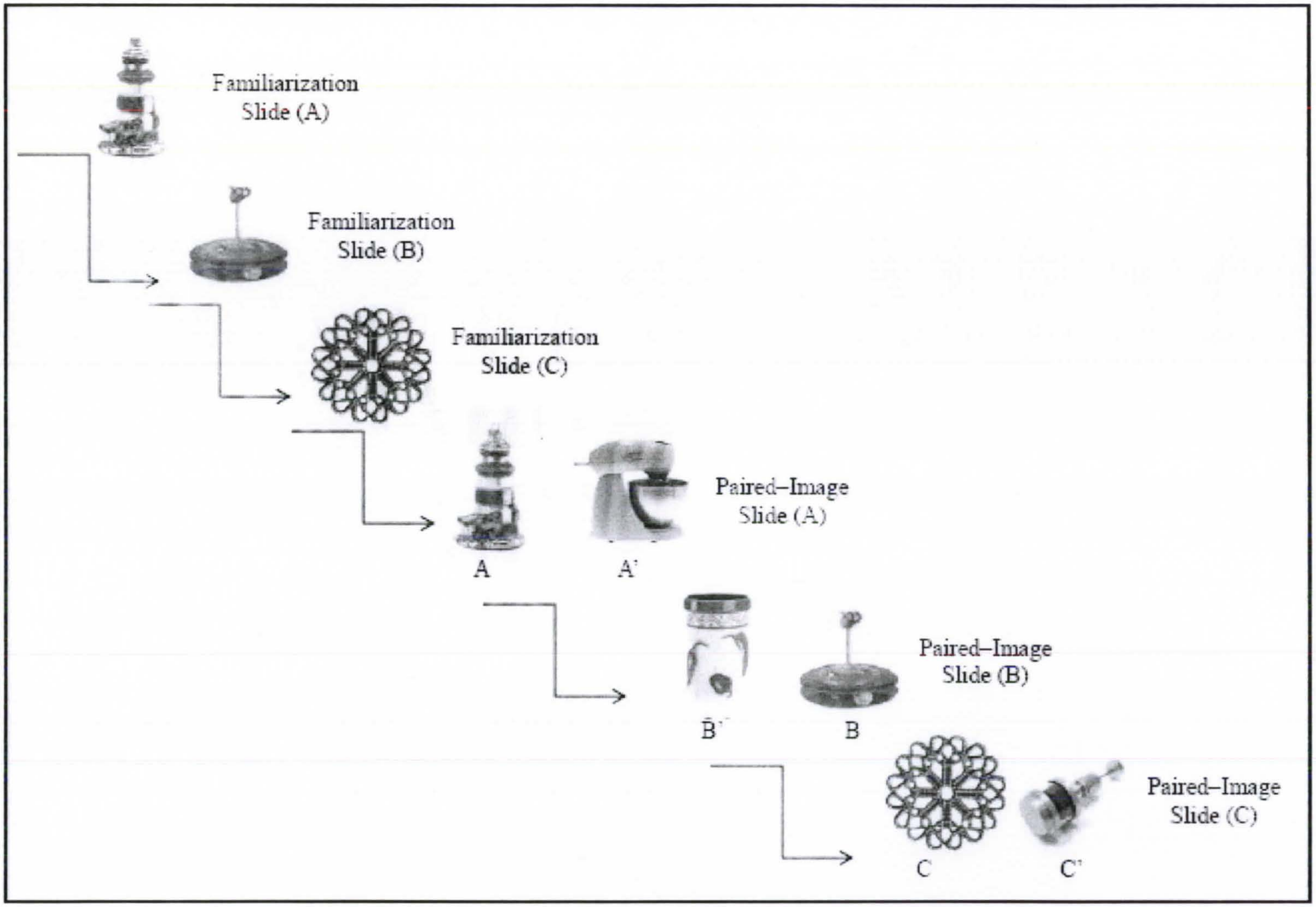

Figure 2-5. Example of a Test Phase with Span Length 3 in the Visual Recognition Memory task.

comparison group is reported in Chapter III and reliability coding information for the 8.5-month-old normal-hearing infants is reported in Chapter V. For all 3 participant groups, there was high coding agreement between the two coders, with correlations ranging from .96 to 1.00.

The coded files were then run through an Excel Macros program, which calculated looking times for each trial. The calculations included the total looking time during each trial (discounting any time the child looked off-screen) and the amount of time looking at the target and non-target for each trial. The looking time for a stimulus during trial X was the total time the child spent focused on that stimulus, which was calculated by combining each look within trial X (if there were multiple looks on the same trial). The primary dependent variable was the time spent looking at the target image, as a proportion of the total time looking (target + non-target) during the trial.

Calculation of Effect Size

An effect size (Cohen's *d*) was calculated for each of the statistics in this dissertation. When calculating *d* from the means and standard deviations, the following formula was used:

$$d = (Y_1 - Y_2) / s_p,$$

where Y_1 is the mean value of the dependent measure for the deaf group, Y_2 is the mean value for the normal-hearing comparison group, and s_p is the pooled standard deviation across the two groups (Hedges & Olkin, 1985). For *t* test analyses, *d* was calculated as

$$d = t * \sqrt{(n_1 + n_2) / (n_1 n_2)},$$

where t is the reported statistic value, n_1 is the sample size for the deaf group, and n_2 is the sample size for the normal-hearing comparison group (Lipsey & Wilson, 2001). For correlation analyses, Fisher's z was the effect size used, and was calculated as

$$z = \frac{1}{2} [\log_e (1 + r) - \log_e (1 - r)],$$

where r is the Pearson correlation (Lipsey & Wilson, 2001).

Language and Communication Measures

In order to measure the extent to which early nonverbal cognitive abilities are correlated with English spoken language abilities, infants were assessed using the MacArthur-Bates Communicative Development Inventories—both the 'Words and Gestures' (CDI-1) and the 'Words and Sentences' (CDI-2) forms (Fenson et al., 2006). These are parental reports of English vocabulary and have been validated for use in a population of deaf children who use cochlear implants who were as old as 66 months (Thal, DesJardin, & Eisenberg, 2007).

Words and Gestures form. The 'Words and Gestures Form' (CDI-1) is primarily a receptive vocabulary questionnaire that consists of phrases, vocabulary words, and communicative gestures. The first section is comprised of 28 common phrases (e.g. "Are you hungry?") and the parent marks whether the child understands each of the phrases. The second section is comprised of 396 vocabulary items (e.g. "school") and the parent can mark whether their child understands each of the items or whether their child understands and says those items. The final section of the questionnaire is comprised of 63 different actions and gestures that the child may use for communication (e.g. shrugging to indicate "all gone"). This section also includes imitative actions (e.g. trying to dig with a shovel).

Words and Sentences form. The 'Words and Sentences Form' (CDI-2) is a productive vocabulary questionnaire that has 680 vocabulary items broken into many different sections by semantic categories and/or grammatical roles (e.g. foods, pronouns). There are also grammatical items on the questionnaire, including questions about the general use of grammatical markers (e.g. plural '*s*'), questions about over-regularization, and 37 sentence complexity items—each with 2 options that differ in their grammatical complexity. For example, one sentence complexity item might have 'Doggy eat' and 'The doggy eats' as the two choices. The parent is to choose the option that most closely maps onto their child's current language ability.

The parents of both deaf and normal-hearing infants were asked to fill out the CDI-1 or CDI-2 (depending on the child's age) at the time of participation and again at later time points to report their child's current English vocabulary abilities. Parents of deaf children were instructed to specify whether their child understood/spoke the word manually (M), verbally (V), or both (B). The studies in this dissertation focus on spoken language, so only words marked as V or B were included in analyses.

CDI data collection: 8.5-month-old infants. Parents filled out a CDI-1 at the time of participation (when approximately 8.5 months old) and then were mailed a follow-up CDI-1 approximately 5 months after participating in the study (when approximately 13.5 months old). Parents were sent CDI-2s approximately 9, 15, and 20 months after participating in the study (when children were approximately 17.5, 23.5, and 28.5 months old, respectively). On the CDI-1 the dependent measures were Vocabulary Comprehension—number of words comprehended out of 396—and Gestural Comprehension—number of gestures understood or produced out of 63. On the CDI-2 both vocabulary and grammatical measures were analyzed.

The vocabulary measure was calculated from the number of words the child was reported to produce (out of 680). There were three grammar measures utilized. The first measure (Inflection) was the use of regular inflection (e.g., adding '-ing' to verbs to mark progressive tense). The Inflection score was calculated from the responses on Word Endings/Part 1. Responses of 'Not Yet' were worth 0 points, responses of 'Sometimes' were worth 1 point, and responses of 'Often' were worth 2 points, for a total score ranging from 0–8. The second grammar measure (Irregulars) was the number of irregular word forms the child produced (e.g., went). The Irregulars score was simply a tally of the number of irregular verb and noun items the parent checked on the Word Forms section, for a total score ranging from 0–25. The third grammar measure (Over-Regulars) was whether the child was producing any over-regularization errors (e.g., mouses). The Over-Regulars score was coded dichotomously as either a 0 or a 1 depending on whether parents checked any items in Word Endings/Part 2.

CDI data collection: Deaf infants. Parents of deaf infants filled out a CDI-1 at the time of participation and then were mailed a follow-up CDI-1 when their child had been using a cochlear implant for 2 weeks or less. Parents were sent monthly CDIs for the first 6 months that their child was using a cochlear implant, followed by additional CDIs at 7-8 months of implant use, 9 months of implant use, 10-11 months of implant use, 12 months of implant use, 15 months of implant use, and 18 months of implant use. Parents were sent a CDI-1 until their child was producing 43 or more words (for boys) or 67 words (for girls). Once a child reached those productive vocabulary milestones, parents were sent a CDI-2 for all subsequent time points.

Collecting CDIs after a set amount of time (rather than at specified ages) means that the deaf children were different chronological ages at each CDI time point, due to the variability in their age at cochlear implantation. Collecting data in this manner provided the opportunity to analyze the effect of *time* on deaf children's spoken language development, rather than the effect of *chronological age*. This is an important trade-off in order to better understand the efficacy of the intervention (i.e., getting a cochlear implant).

CDI dependent variables. The CDIs yield raw scores. Standardized percentile scores for different-aged children on the two forms of the CDI have also been published (Fenson et al., 2006). I believe that raw scores are a more appropriate measure for children at the younger age ranges because there is more variability in their raw scores than in their percentile scores. Percentile scores are more appropriate when there is a wider age range, or when children are in the later stages of language development. However, for the sake of consistency, the same measure was chosen—raw vocabulary—at each of the follow-up ages. For the CDI-1 the Vocabulary Comprehension and Gestures scores were used as the outcome measures. For the CDI-2 the Vocabulary Production score was used for vocabulary measure and the use of regular inflection was used as the grammar measure (see Ullman, 2004).

The goal of correlating CDI scores with performance on the VSL and VRM tasks was to determine whether performance on the VSL and/or VRM tasks explains significant variability in children's spoken language outcomes. Therefore the use of the CDIs is somewhat limiting, because it does not represent the child's total vocabulary. A recent article has suggested a solution to that problem. Mayor and Plunkett (2011) developed a mathematical correction that can be applied to reported CDI scores to estimate a child's total vocabulary. They used existing diary studies of early vocabulary development in individual children (Haggerty, 1929; Robinson & Mervis, 1999; Roy, Frank, & Roy, 2009) to validate the mathematical correction. The formula for this correction is

$$Vocabulary_{estimated} = \sum_{i=1}^{W} p(w_i) = \frac{1}{N} \sum_{j=1}^{N} vocabulary(j)$$

where W is the number of words on the CDI, *vocabulary(j)* measures the CDI score of infant j, and N represents the number of infants (see Appendix 2 in Mayor & Plunkett, 2011). A web calculator was used, available on the author's website (http://www.bcbl.eu/cdi/), to calculate the total estimated vocabulary for each CDI-2. Mayor and Plunkett concluded that the CDI can serve as a basis for determining a child's total vocabulary. Because ultimately the interest is in how infants' performance on the VSL and VRM tasks relates to their spoken language outcomes, and not just to their reported CDI vocabulary, the Mayor and Plunkett (2011) correction was used to estimate total productive vocabulary for all of the time points in which the CDI-2 was collected. These total vocabulary estimates were then used as the vocabulary outcome measures for the correlation analyses.

Issues to consider. The reliability and validity of the CDIs were demonstrated in numerous early studies (Camaioni, Caselli, Longobardi, & Volterra, 1991; Dale, 1991; Dale, Bates, Reznick, & Morisset, 1989; Jackson-Maldonado, Thal, Marchman, Bates, & Gutierrez-Clellen, 1993; O'Hanlon, Washkevich, & Thal, 1991) and parents have been generally found to be good judges of whether their child understands and/or produces a given word (Fenson et al., 2006; Ring & Fenson, 2000; Styles & Plunkett, 2009). These early studies compared laboratory measures of vocabulary and grammar to the parent-report measures and found moderate to high reliability in all cases. In addition, other studies have found that parent report measures correlate with spontaneous speech (Bornstein & Haynes, 1998; Corkum & Dunham, 1996; J. F. Miller, Sedey, & Miolo, 1995), that parent-report measures (including checklists) correlate with laboratory measures and standardized assessment (Bates & Carnevale, 1993; Bornstein & Haynes, 1998; Chaffee, Cunningham, Secord-Gilbert, Elbard, & Richards, 1990; Fenson et al., 1994; J. F. Miller et al., 1995; Saudino et al., 1998), that parent diaries correlate with checklists (Reznick & Goldfield, 1994), and that observed child speech correlates with experimenter assessments (Bornstein & Haynes, 1998).

The primary limit of the CDIs is that they cannot distinguish between imitations and spontaneous speech, nor the range of contexts in which particular words are used. There is also a question of whether the distribution of scores is appropriate for children who are outside of the norming age range (older than 30 months). For the current dissertation the CDIs were used with deaf children who were as old as 42 months old at follow-up. In a previous study the CDIs were used and validated in a group of deaf children who use cochlear implants who were as old as 66 months (Thal et al., 2007), so I am reasonably confident in the use of this measure with the children in these studies.

CHAPTER III

AN INVESTIGATION OF THE RELATION BETWEEN EARLY AUDITORY DEPRIVATION AND NONVERBAL COGNITIVE ABILITY

This chapter presents an investigation of the impact of deafness on visual recognition memory and visual sequence learning.

In order to test whether early deafness is related to nonverbal cognitive ability, deaf infants were tested on two nonverbal cognitive tasks – the VSL task (Study 1) and the VRM task (Study 2) – prior to cochlear implantation. Their performance was compared to that of hearing infants who were approximately the same chronological age. Significant differences between the hearing age-matched and the deaf infants, such as the deaf infants having slower reaction times or an inability to learn the visual sequence in the VSL task, and the inability to recognize familiarized images in the VRM task, would suggest that deafness is negatively related to general cognitive processes, at least the two processes tapped through these two tasks. This pattern of results would be consistent with results from a recent study suggesting general cognitive differences between deaf and hearing infants prior to cochlear implantation (Shafto et al., under review).

If the deaf and hearing infants perform similarly on the two experimental tasks, this would suggest that deafness is not related to visual sequence learning and visual recognition memory. It is also possible that deaf infants would show a different pattern of performance compared to the hearing infants on only one of the two tasks. That pattern of results would suggest that deafness is only related to some general cognitive processes.

Study 1: Visual Sequence Learning

Participants

Deaf infants. The 19 deaf infants (11 female) were recruited through the Heuser Hearing Institute in Louisville, KY, and the Infant Speech Lab at the Indiana University School of Medicine in Indianapolis, IN. One additional female infant was tested, but was excluded from analyses for crying/fussing. The deaf infants ranged in age from 7.9 to 22.6 months old ($M = 15.0$, $SD = 4.6$ months) at the time of test; all infants had congenital severe to profound deafness and were either scheduled to receive a cochlear implant or had a cochlear implant activated within 24 hours of participation in this study. All infants were diagnosed with hearing loss before the age of 21 months. Eighteen of the infants used bilateral hearing aids and one infant had already received a cochlear implant, which had been activated the day before participating in the study. See Table 3-1 for individual demographic information.

Infants with normal hearing. Each infant in the deaf group was matched on chronological age (+/- 1 month) to a normal-hearing infant. The hearing group consisted of 19 infants (12 female) who ranged in age from 8.1 to 22.6 months ($M = 15.0$, $SD = 4.6$ months) at the time of testing. There were 5 additional infants tested (4 female) whose data were not included in the analyses due to fussiness ($n = 2$), refusing to sit on their mother's lap ($n = 2$), and due to experimenter error ($n = 1$). All infants had passed a newborn hearing screening, had no history of recurrent acute or chronic otitis media, and were not diagnosed with nor suspected of developmental delays by their pediatricians.

General Procedure

All infants' testing was completed in less than a half hour and was done in a sound booth with the parent present. In addition to the experimental task, parents also filled out a background questionnaire to document hearing status and information related to hearing and medical history.

Visual Sequence Learning (VSL) task. The task Apparatus, Stimuli, and Procedure are described in detail in Chapter II. Details about the data collection, eye movement coding, and the calculation of the dependent variables are also described in Chapter II.

VSL Analyses

In order to test for the relation between auditory deprivation and nonverbal cognitive ability, deaf infants' performance was compared to normal-hearing infants' performance on the VSL task. For the VSL task success is defined as 'learning' the sequence, or having a decrease in RT from Phase 1 to Phase 2. For the paired *t*-tests, Cohen's *d* effect sizes were calculated using an online calculator that corrects for dependence between means (http://www.cognitiveflexibility.org/effectsize/). For all other analyses, Cohen's *d* was calculated using the formulas outlined in Chapter II.

VSL Results

Two sets of analyses were conducted. First, children's performance on the VSL task was analyzed to determine whether they learned the spatiotemporal sequence.

Table 3-1

Demographic Information for Deaf Participants

ID	Sex	Age at Stim (Months)	Aided PTA	Etiology	Comm Mode
A	M	17.30	57 dB HL	unknown	TC
B	M	13.85	90 dB HL	genetic (mother's cousins)/Mondini/LVA	TC
C	M	10.20	83 dB HL	unknown	oral-only
D	M	16.88	59 dB HL	unknown	oral-only
E	F	11.25	90 dB HL	unknown	oral-only
F	F	16.78	63 dB HL	unknown	oral-only
G	F	16.58	82 dB HL	genetic (uncle and cousin)/Mondini/LVA	oral-only
H	F	21.58	73 dB HL	Mondini/connexin 26 and 30	oral-only
I	M	23.13	90 dB HL	unknown	ASL[1]
J	F	20.72	47 dB HL	unknown/febrile seizures starting at 8 months	oral-only
K	F	16.97	90 dB HL	CMV	oral-only
L	F	16.12	57 dB HL	unknown	oral-only
M	F	10.10	90 dB HL	unknown	oral-only
N	F	13.68	90 dB HL	probable CMV	oral-only
O	M	21.68	37 dB HL	unknown	oral-only
P	F	23.26	71 dB HL	unknown	other[2]
Q	F	12.53	43 dB HL	CMV	oral-only
R	M	18.19	44 dB HL	connexin 26	oral-only

Note: For etiology Mondini = Mondini syndrome; LVA = Large vestibular aqueduct syndrome ; CMV = cytomegalovirus; [1]child has cerebral palsy and parents are not native ASL signers; [2]child was exposed to mostly ASL signs early on, although mother is not a native or fluent ASL signer; after about 9 months of CI use, mother switched to an oral-only focus.

Second, we compared deaf infants' performance on the VSL task to that of the normal-hearing age-matched infants.

Did children learn the sequence? We investigated this question separately for the two groups. Raw data are presented in Figures 3-1 and 3-2.

Deaf infants. In order to answer this question for the deaf infants, we conducted 2 paired-samples t tests: one on the change in RT from Phase 1 to Phase 2 [$t(18) = -0.35$, $p = .973$, $d = -.02$] and one on the change in the number of correct anticipatory looks from Phase 1 to Phase 2 [$t(18) = -1.02$, $p = .322$, $d = -.24$; see Table 3-2 for descriptive statistics]. There was no significant difference between the RTs or the number of correct anticipatory looks for the two phases. This suggests that as a group, the deaf infants may not have learned the visual sequence. However, there was a lot of variability in children's performance with some infants ($n = 12$) demonstrating clear patterns of learning (any decrease in RT from Phase 1 to 2, or positive RT difference score).

Hearing infants. In order to answer this question for the hearing infants, we again conducted 2 paired-samples t tests: one on the change in RT from Phase 1 to Phase 2 [$t(18) = -1.11$, $p = .279$, $d = -.26$] and one on the change in the number of correct anticipatory looks from Phase 1 to Phase 2 [$t(18) = -1.53$, $p = .145$, $d = -.35$; see Table 3-2 for descriptive statistics]. There was no significant difference between the RTs or the number of correct anticipatory looks for the two phases. This suggests that as a group, the hearing infants may not have learned the visual sequence. As with the deaf infants, there was a lot of variability in infants' performance with some infants ($n = 11$) demonstrating clear patterns of learning (a decrease in RT from Phase 1 to 2, or positive RT difference score).

Did the two groups perform differently? In order to answer this question we first calculated the proportion of change in median RTs between the two phases—Phase 1 RT minus Phase 2 RT (hereafter the 'RT difference score')—for each child. We compared the average RT difference score for the two groups using a dependent-samples t test. The result of this test [$t(18) = -0.47, p = .646, d = -.10$] yielded a nonsignificant difference between the two groups in their performance on the VSL task.

One possibility is that the wide age range of our participants could have affected performance on the VSL task. However, according to a linear regression analysis, there was no effect of chronological age on RT difference score [$F(1, 36) = .17, p = .679, d = .13$; see Figure 3-3], despite the wide age range of our participants (8 – 23 months old). A second linear regression was conducted in order to determine whether hearing status (deaf or normal hearing) predicted RT difference score. The result of this analysis was also nonsignificant [$F(1, 36) = .11, p = .743, d = .11$; see Figure 3-3].

A power analysis was conducted prior to beginning the study and it was determined that in order to detect a medium effect size (d =.40) with a p value of .05, a total sample size of 78 infants is needed. However, in a recent study we found that same effect size in a comparison of just 23 deaf and 23 hearing infants on a visual habituation task (d = .43 for overall looking time; see Shafto et al., under review). Because the results from the current study are results from an even smaller sample, the lack of a significant group difference could simply be due to a lack of statistical power.

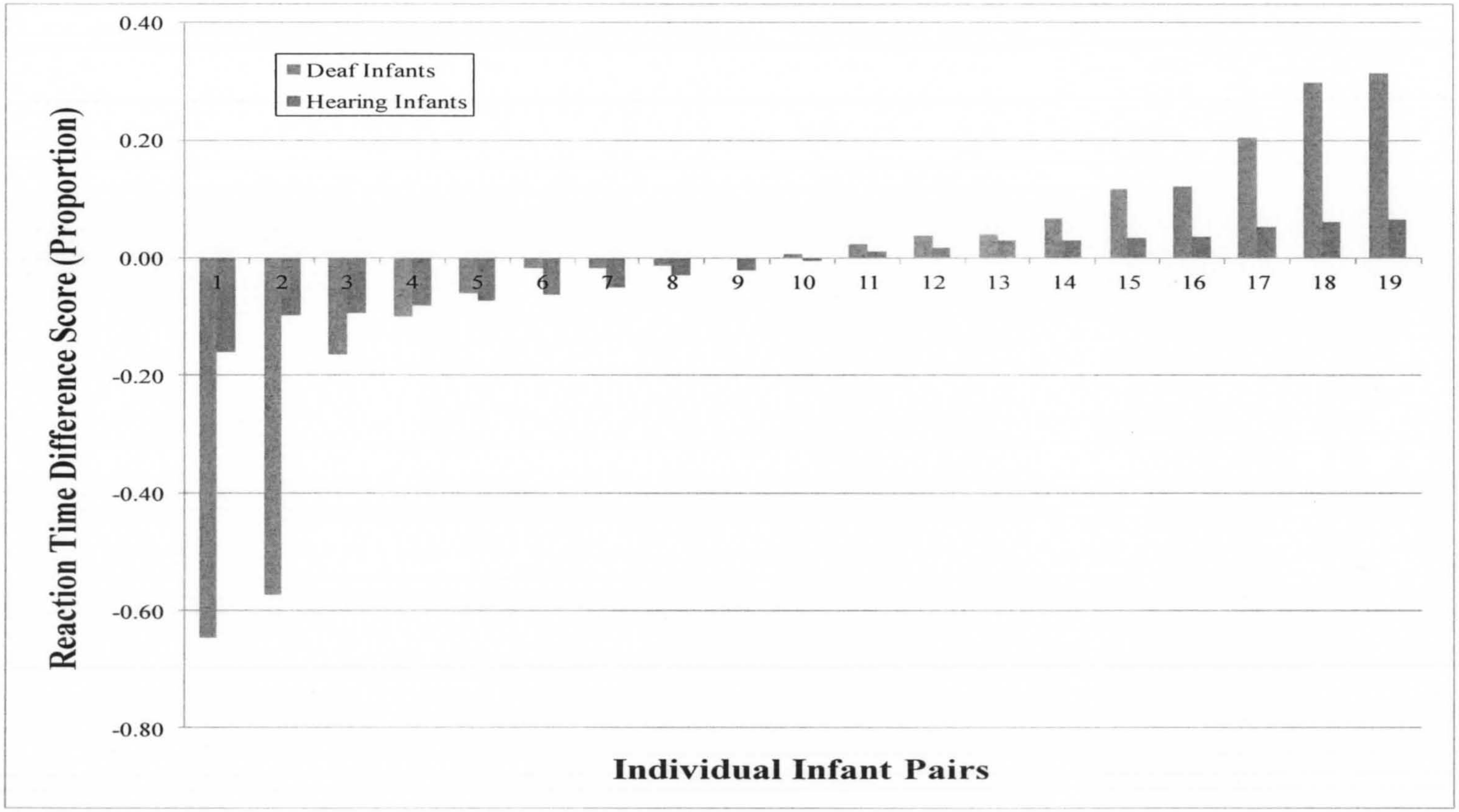

Figure 3-1. RT difference score on the VSL task for individual infants.

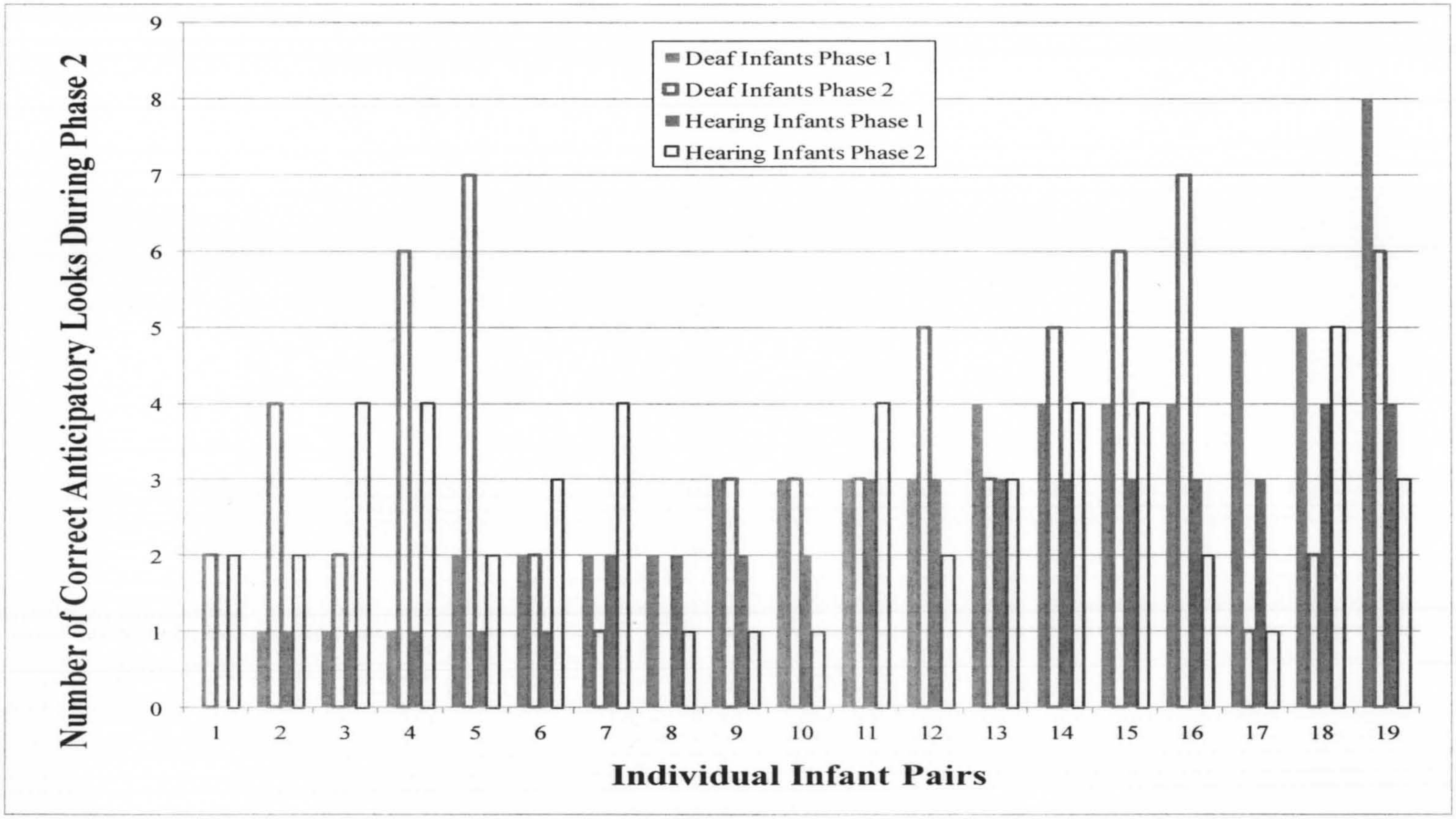

Figure 3-2. Correct anticipatory looks in Phases 1 and 2 of the VSL task for individual infants.

Table 3-2

Descriptive Statistics for Deaf and Hearing Infants on VSL Task Measures

Measure	Median RT in Phase 1 (sec)	Median RT in Phase 2 (sec)	Correct Anticipatory Looks in Phase 1	Correct Anticipatory Looks in Phase 2
Deaf Infants				
M	0.32	0.33	3.00	3.58
SD	0.51	0.67	1.86	2.14
Range	-1.17 - 1.60	-0.58 - 2.02	0 - 8	0 - 7
Hearing Infants				
M	0.40	0.45	2.21	2.74
SD	0.32	0.35	1.13	1.28
Range	0.13 - 1.60	0.08 - 1.35	0 - 4	1 - 5

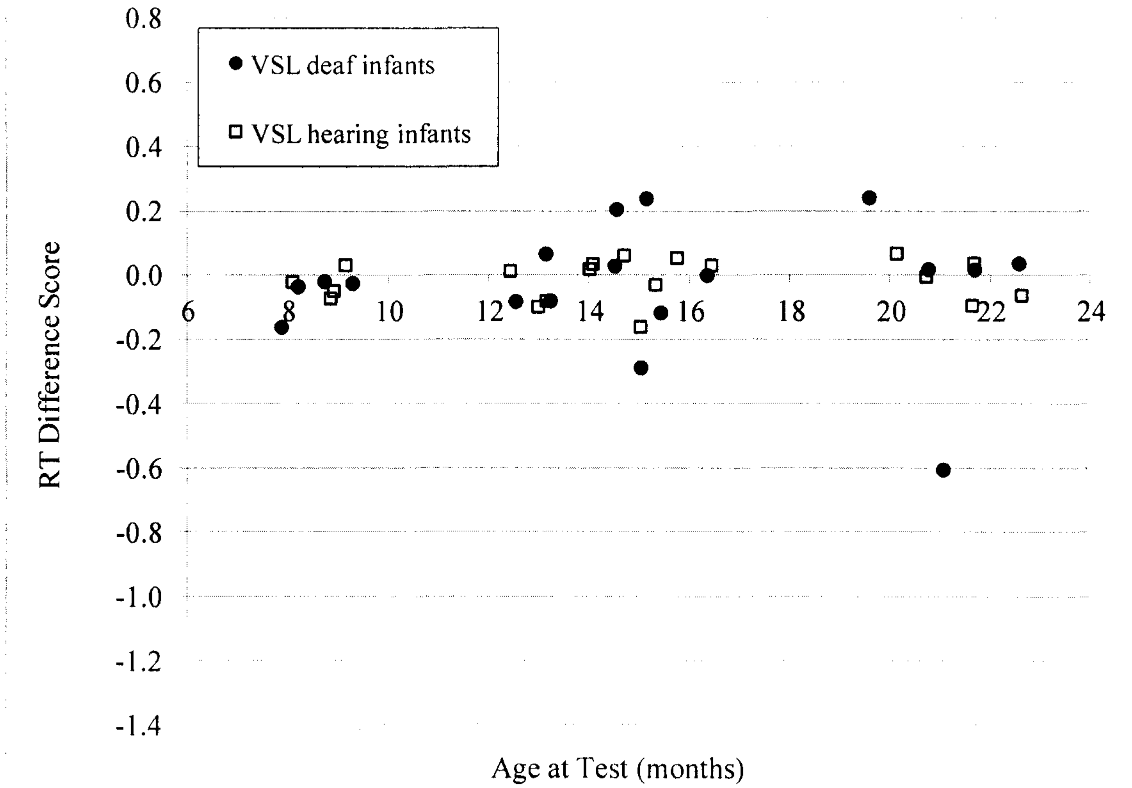

Figure 3-3. RT difference score on the VSL task as a function of age at test.

Study 2: Visual Recognition Memory

Participants

Deaf infants. The 13 deaf infants (8 female) were recruited through the Heuser Hearing Institute in Louisville, KY, and the Infant Speech Lab at the Indiana University School of Medicine in Indianapolis, IN. Four additional infants were tested (3 female), but were excluded from analyses for crying/fussing out. The deaf infants ranged in age from 7.8 to 21.0 months old ($M = 15.0$, $SD = 4.0$ months) at the time of test; all infants had congenital severe to profound deafness and were either scheduled to receive a cochlear implant or had a cochlear implant activated within 24 hours of participation in this study. All infants were diagnosed with hearing loss before the age of 21 months. Twelve of the infants used bilateral hearing aids and one infant had already received a cochlear implant, which had been activated the day before study participation. See Table 3-1 for full demographics.

Infants with normal hearing. Each infant in the deaf group was matched on chronological age (+/- 1 month) to a normal-hearing infant. The hearing group consisted of 13 infants (6 female) who ranged in age from 7.9 to 22.6 months ($M = 15.0$, $SD = 4.1$ months) at the time of testing. There were five additional infants tested (4 female) whose data were not included in the analyses due to fussiness ($n = 3$) and for refusing to sit on her mother's lap ($n = 1$). All infants had passed a newborn hearing screening, had no history of recurrent acute or chronic otitis media, and were not diagnosed with nor suspected of developmental delays by their pediatricians.

General Procedure

All infants' testing was completed in less than a half hour and was done in a sound booth with a parent present. In addition to the experimental task, parents also filled out a background questionnaire to document hearing status and information related to hearing status (e.g., date of identification of hearing loss).

Visual Recognition Memory (VRM) task. The task Apparatus, Stimuli, and Procedure are described in detail in Chapter II. Details about the data collection, eye movement coding, and the calculation of the dependent variables are also described in Chapter II.

Coding reliability. A first coder coded eye movements for all of the trials for all of the infants. Then a second coder coded all trials for a randomly-selected 25 percent of the infants (n = 5 for the deaf infants; n = 5 for the normal-hearing infants) for reliability. The second coder was blind to the purpose of the experiment. The correlations between coders on looking time ranged from 0.965 to 1.0 with an average correlation of 0.98.

VRM Analyses

In order to test for a relation between auditory deprivation and nonverbal cognitive ability, deaf infants' performance was compared to normal-hearing infants' performance on the VRM task. On the VRM task, success is defined as recognizing the familiarized images, as indicated by longer looking times to the novel objects in the paired–comparison test trials. The primary dependent variable was the time spent looking at the target image (the novel one), as a proportion of the total time looking (target + non-target; novel + familiar) during the trial, which was then multiplied by 100 to be a percentage (hereafter, the novelty score; see Rose et al., 2001). A novelty score was calculated for each test trial (a total of 5). Then an average novelty score was calculated for the span-2 test phase, which was an average of the two span-2 test trials, and a separate novelty score was calculated for the span-3 test phase, which was an average of the three span-3 test trials. For the paired *t*-tests, Cohen's *d* effect sizes were calculated using an online calculator that corrects for dependence between means (http://www.cognitiveflexibility.org/effectsize/). For all other analyses, Cohen's *d* effect sizes were calculated using the formulas outlined in Chapter II.

VRM Results

Two sets of analyses were conducted. First, we analyzed infants' performance on the VRM task to determine whether they remembered the familiarized images (see Table 3-3 for VRM task descriptive statistics). Second, we compared deaf infants' performance on the VRM task to that of the normal-hearing age-matched infants. The normal-hearing and deaf infants are matched on chronological age so significant differences in the performance of the two groups would suggest a significant relation between early auditory deprivation and performance.

Did children remember the images? We investigated this question separately for the two groups. Raw data are presented in Figures 3-4 and 3-5.

Deaf infants. The expectation was that, for each test trial, infants who remembered the familiarized images would have a novelty score significantly above chance. We therefore conducted one-sample *t* tests, comparing novelty scores to chance performance (50%). We ran these analyses first on the two test trials in the span-2 test phase [$t(12) = -0.57$, $p = .581$, $d = -0.22$; $t(12) = -0.49$, $p = .632$, $d = -0.19$; listed in chronological order]. We then ran these comparisons on the three test trials in the span-3 test phase [$t(12) = 0.67, p = .516, d = 0.26$; $t(12) = 0.21, p = .836, d = 0.08$; $t(12) = -0.13$, $p = .898, d = -0.05$; listed in chronological order]. Contrary to expectations, the deaf infants did not demonstrate a significant novelty preference during the two test phases. This suggests that as a group, the deaf infants did not remember the visual stimuli with which they were familiarized. Overall there was a lot of variability in performance with several infants demonstrating clear patterns of remembering—demonstrating either a significant novelty effect (looking significantly longer at the novel stimulus) or a significant familiarity effect (looking significantly longer at the familiar stimulus). This is in line with previous studies suggesting that infants in our age range should be able to easily discriminate familiarized images from novel images (see e.g., Rose et al., 2001).

Normal-hearing infants. Again, the expectation was that, for each test trial, infants who remembered the familiarized images would have a novelty score significantly above chance. We therefore conducted one-sample *t* tests, comparing novelty scores to chance performance (50%). We ran these analyses first on the two test trials in the span-2 test phase [$t(12) < .001, p = 1.00, d < .001$; $t(12) = 0.19, p = .851, d = 0.07$; listed in chronological order]. We then ran these comparisons on the three test trials in the span-3 test phase [$t(12) = 1.93, p = .077, d = 0.76$; $t(12) = -0.02, p = .982, d = -0.008$; $t(12) = -0.01, p = .989, d = -0.004$; listed in chronological order]. Like the deaf infants, the normal-hearing infants did not demonstrate a significant novelty preference during the two test phases, although the marginal effect on the first test trial of span-3 could have led to proactive interference on the subsequent test trials. This suggests that as a group, the hearing infants did not remember the visual stimuli with which they were familiarized. As with the deaf infants, there was a lot of variability in performance with several infants demonstrating clear patterns of remembering—demonstrating either a significant novelty effect (looking significantly longer at the novel stimulus) or a significant familiarity effect (looking significantly longer at the familiar stimulus).

Did the two groups perform differently? In order to answer this question we ran matched-pairs (dependent) t tests comparing the novelty scores for the two groups. First the two groups were compared on the two test trials in the span-2 test phase and there were no differences between the groups [$t(12) = -0.64$, $p = .535$, $d = -0.20$; $t(12) = -0.55$, $p = .592$, $d = -0.15$; listed in chronological order]. There were also no significant differences in novelty score for the test trials in the span-3 test phase [$t(12) = -0.48$, $p = .637$, $d = -0.13$; $t(12) = 0.22$, $p = .831$, $d = 0.06$; $t(12) = -0.11$, $p = .913$, $d = -0.03$; listed in chronological order]. This suggests that there were no significant differences in visual recognition memory between the deaf infants and a group of hearing infants matched on chronological age.

One possibility is that the wide age range of our infants could have affected performance on the VRM task. According to a series of linear regression analyses, there were no significant effects of chronological age on the average span-2 novelty score [$F(1, 24) = 11.08$, $p = .234$, $d = 1.26$; see Figure 3-6], or the average span-3 novelty score [$F(1, 24) = 2.07$, $p = .507$, $d = 0.55$; see Figure 3-7] despite the wide age range of our participants (8 – 23 months old). A second linear regression was conducted in order to determine whether hearing status (deaf or normal hearing) predicted novelty score. The result of these analyses [span-2 test phase $F(1, 24) = .42$, $p = .523$, $d = .25$; span-3 test phase $F(1, 24) = 0.10$, $p = .758$, $d = .12$] were also nonsignificant (see Figures 3-6 and 3-

7). However, because these are results from a small sample, the lack of a significant group difference could simply be due to a lack of statistical power.

Discussion

Quite a lot of recent evidence suggests that in addition to spoken language, general cognitive abilities may also be related to early deafness (e.g., Marschark & Hauser, 2008; Pisoni, 2008). Therefore we hypothesized that if deafness is related to general cognitive ability, then the deaf infants would perform more poorly than same-aged hearing infants on the VSL and VRM tasks. In the current sample there were no significant differences in VSL or VRM performance between the two groups. Interestingly, the same-aged hearing infants did not demonstrate group learning on either the VSL or the VRM tasks. This pattern of results is similar to the results from a study of normal-hearing infants aged 8.5 months (see Chapter IV and Shafto et al., 2012). In the VSL study the performance of infants who learned the visual sequence may have been cancelled out by the performance of infants who did not learn the visual sequence.

These results comparing deaf and normal-hearing infants on the VSL and VRM tasks are inconclusive due to the relatively small sample sizes in the two studies. Also, although there were no significant effects of chronological age on performance, there is still a possibility that the methodology might be less well-suited for older infants. In order to address that possibility, one could examine how performance on the tasks correlates with other measures across the age span. The potential patterns of results that might be obtained with a larger sample are discussed briefly in the General Discussion (Chapter VII).

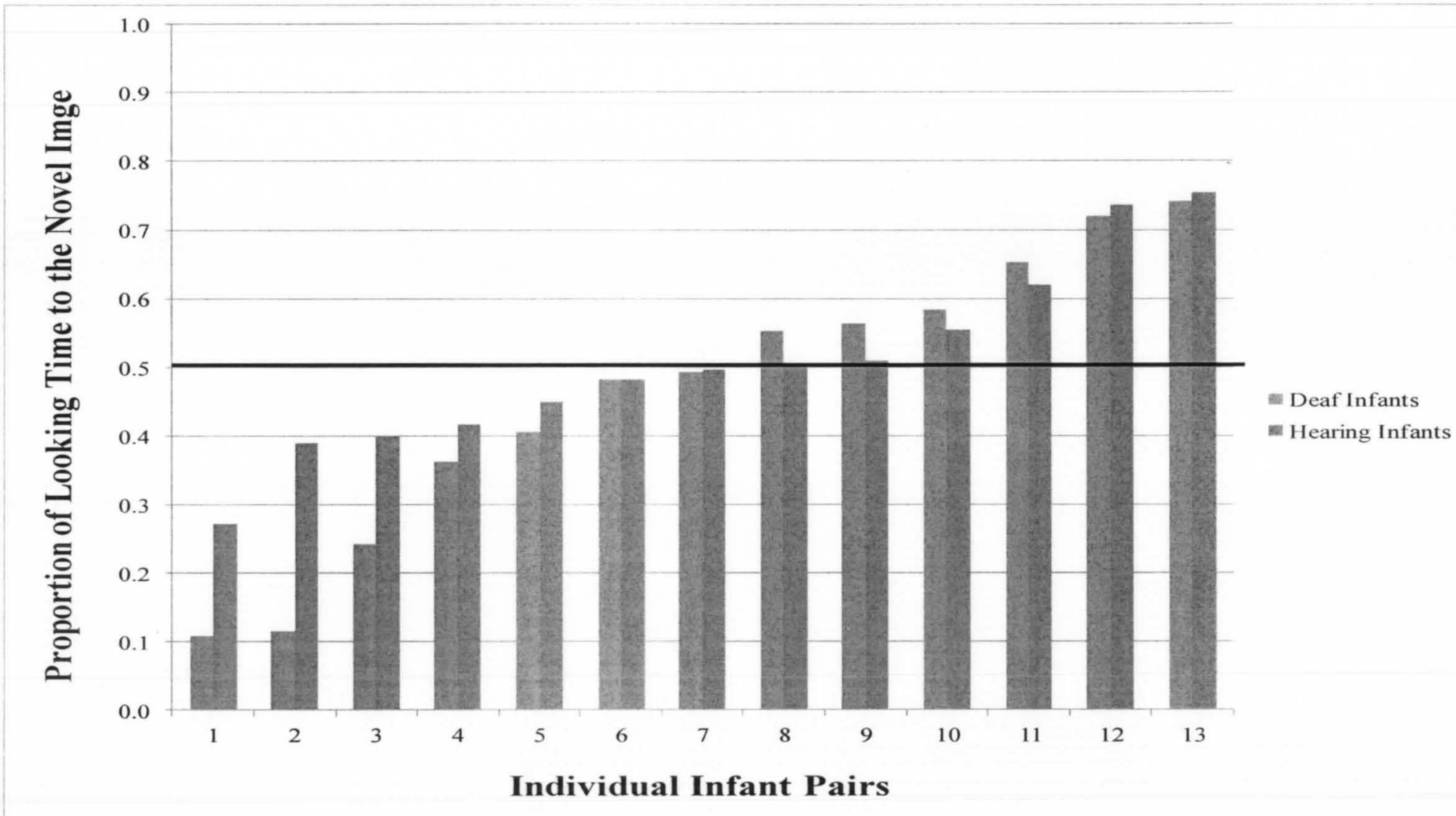

Figure 3-4. Novelty score across the span-2 test trials of the VRM task for individual infants.

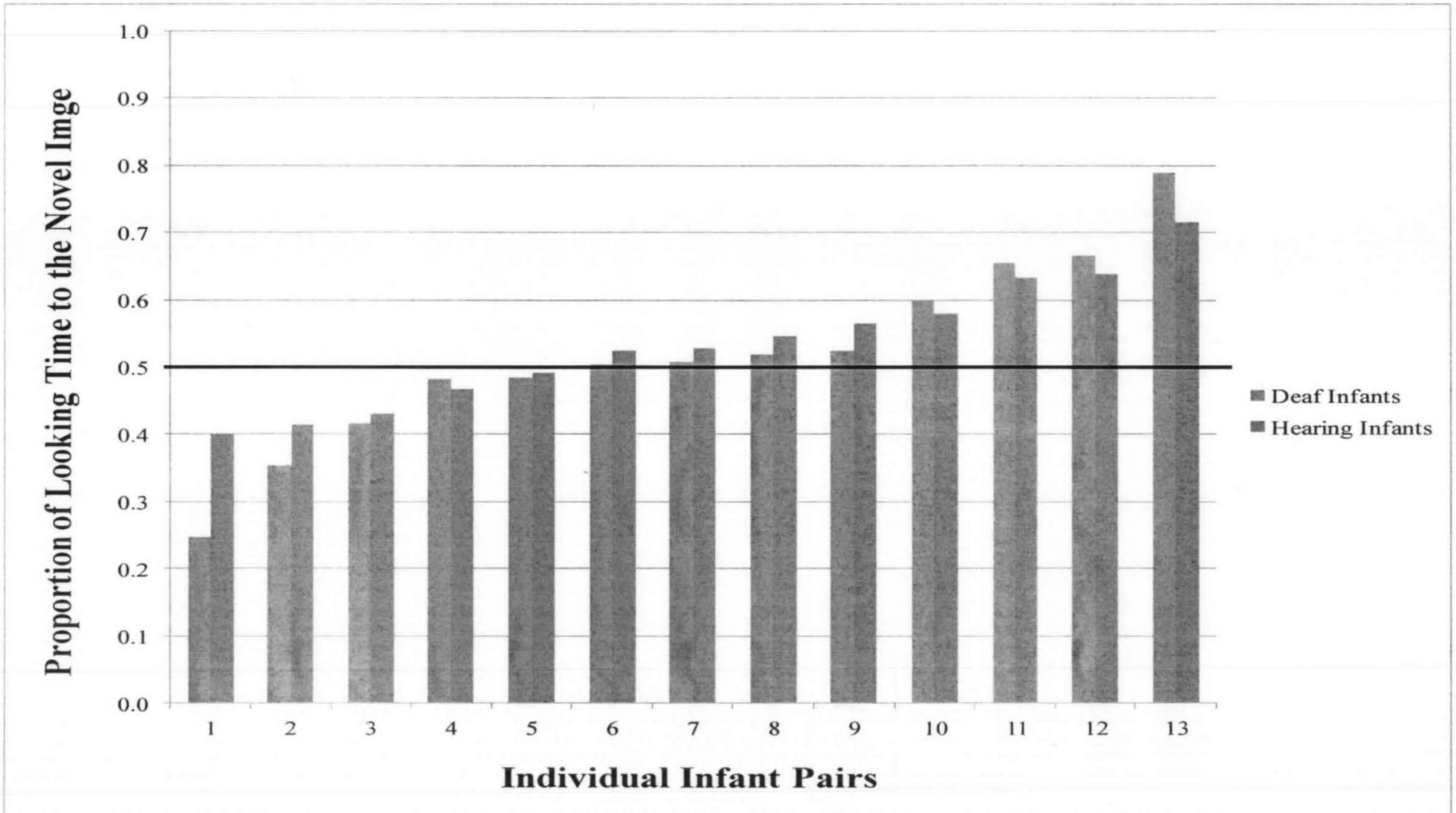

Figure 3-5. Novelty score across the span-3 test trials of the VRM task for individual infants.

Table 3-3

Descriptive Statistics for Deaf and Hearing Infants on VRM Task Measures

	Pre-test Phase		Span-2 Test Phase		Span-3 Test Phase		
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 3
Measure	Novelty Score	Novelty Score	Novelty Score	Novelty Score	Novelty Score	Novelty Score	Novelty Score
Deaf Infants							
M	.54	.57	.46	.46	.55	.52	.49
SD	.18	.24	.24	.28	.27	.33	.32
Range	.25 - .84	.00 - .91	.08 - .95	.00 - .97	.05 - 1.00	.00 - 1.00	.00 - 1.00
Hearing Infants							
M	.52	.58	.50	.51	.60	.50	.50
SD	.12	.20	.14	.23	.19	.24	.19
Range	.34 - .69	.13 - .84	.22 - .69	.14 - .89	.40 - .93	.00 - .86	.23 - .80

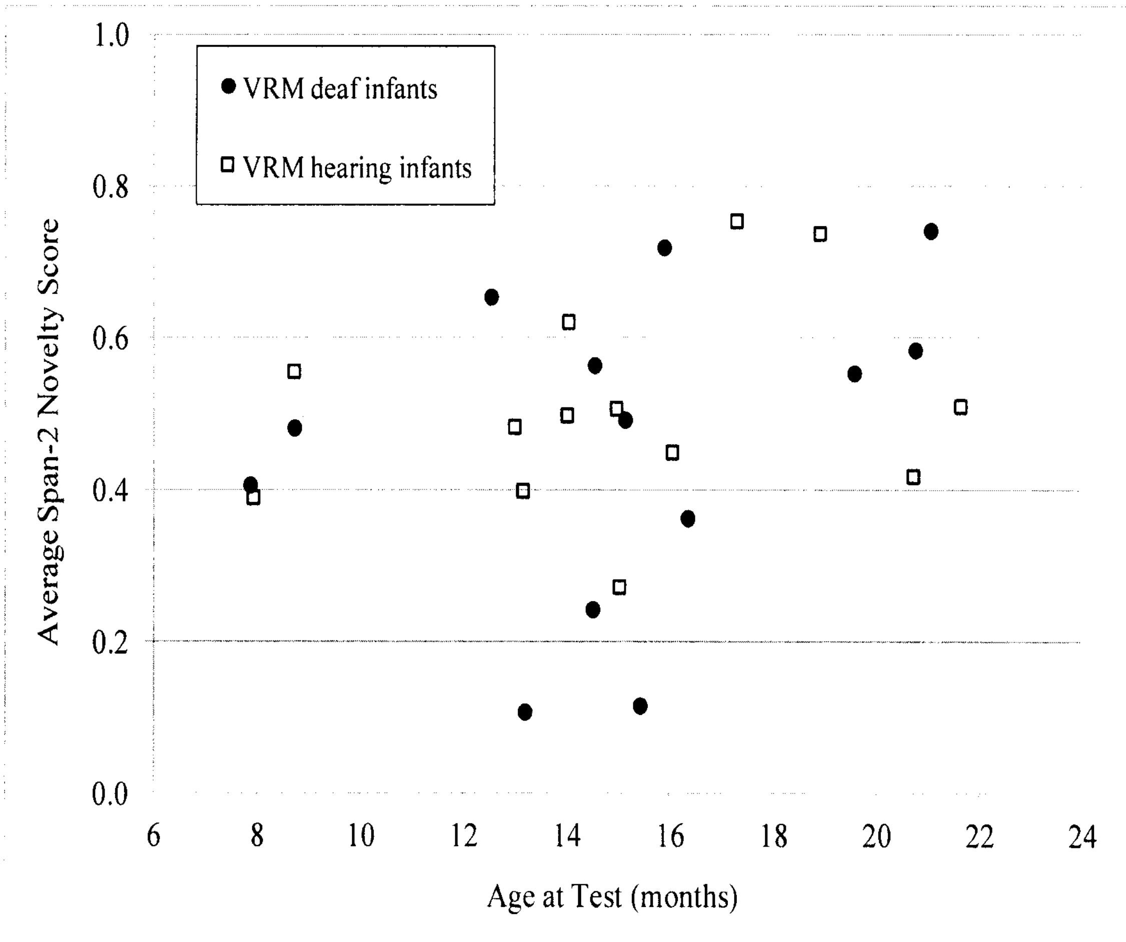

Figure 3-6. Average novelty score on the span-2 test trials of the VRM task as a function of age at test.

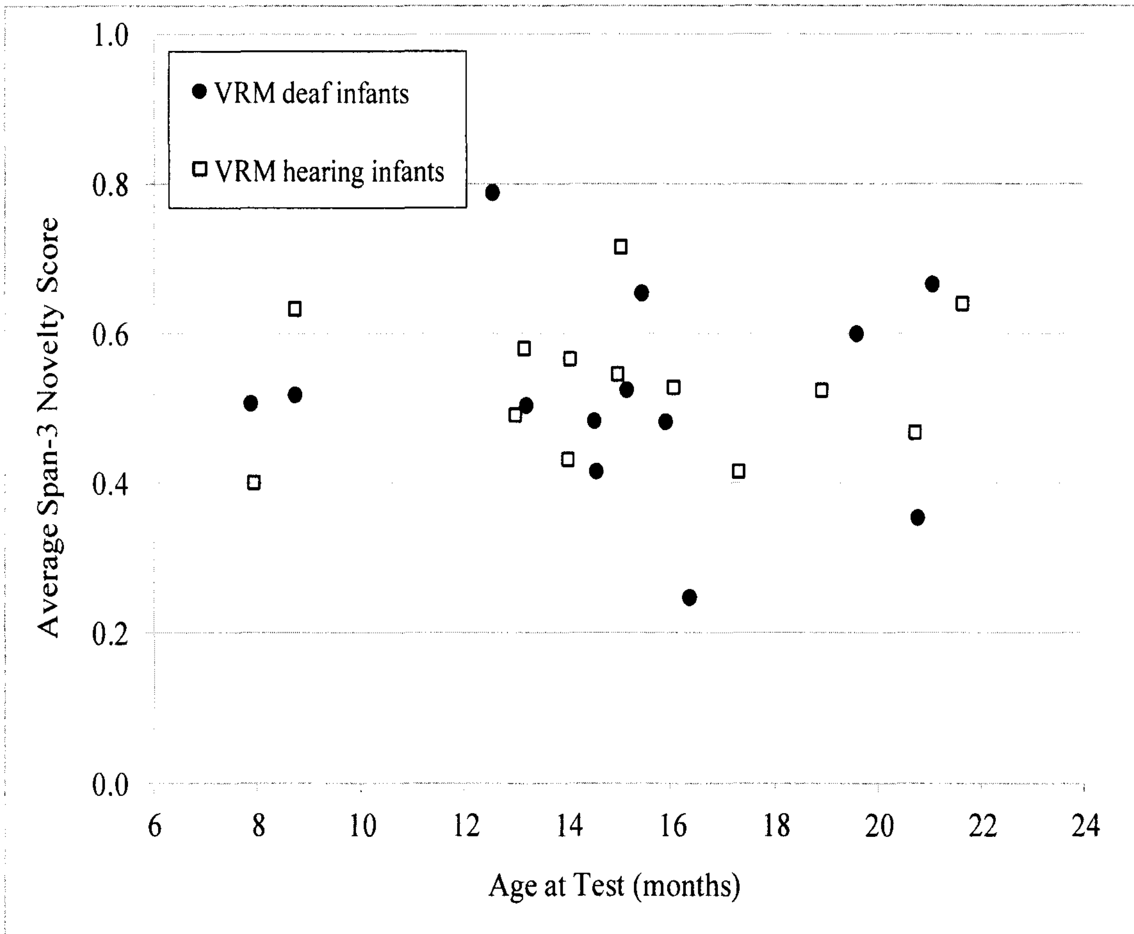

Figure 3-7. Average novelty score on the span-3 test trials of the VRM task as a function of age at test.

Summary

The two studies in this chapter aimed to provide a first step toward addressing the question of whether early deafness is related to nonverbal cognitive processes in deaf infants. Specifically, the goal was to determine whether children who have experienced early auditory and language deprivation (as deaf infants prior to cochlear implantation) have deficits in implicit visual sequence learning or visual recognition memory compared to same-aged infants with typical hearing ability. Results thus far suggest a nonsignificant difference in performance on either task for a moderately-sized sample of deaf infants. In future research a larger sample of deaf infants should be recruited in order to gain a more definitive answer to this research question.

CHAPTER IV

VISUAL SEQUENCE LEARNING IN INFANCY: DOMAIN-GENERAL AND DOMAIN-SPECIFIC ASSOCIATIONS WITH LANGUAGE

This chapter addresses the potential link between visual sequence learning in infancy and spoken language outcomes up to age 30 months for infants with normal hearing ability.

In the present study, visual sequence learning (VSL) and its connection to language development in 8.5-month-old infants is investigated. A novel VSL task was used, which relies on reaction time to assess how well infants learned a simple repeating 3-item spatiotemporal sequence. The task is similar to paradigms used by Haith and colleagues (e.g., Wentworth & Haith, 1998; Wentworth et al., 2002), McMurray (e.g., McMurray & Aslin, 2004), and Kirkham (Kirkham et al., 2007), but was modeled more directly after the paradigm in Clohessy, Posner, and Rothbart (2001). The current study used a 3-item temporal sequence (rather than the 2-item sequences that have been used in most infant studies that relied on reaction time) because it is more complex than a 2-item sequence, and therefore more likely to map onto cognitive processes that were of interest (e.g., language acquisition, which involves complex sequences).

The VSL task assesses infants' ability to learn a sequence of spatial locations. The prediction was that as infants learned the sequence they would get faster at orienting to the next stimulus location in the sequence. At the time of participation, a receptive language measure, the MacArthur-Bates Communicative Development Inventory (Fenson et al., 2006), was also used to probe the relation between VSL performance and language comprehension ability, which is developing well before infants begin to speak. Finally, additional language measures were collected at later time points—at approximately 13.5, 17.5, 23.5, and 28.5 months old—to investigate the predictive relation between VSL and language development in the months after participating in the study.

Method

Participants

The participants were 55 infants (30 female). On the day of testing infants ranged in age from 8.0 to 9.8 months (M = 8.6, SD = 0.46 months) and all had passed their newborn hearing screening. An additional 14 infants (9 female) were tested, but were excluded from analyses for crying/fussing ($n = 9$), being exposed to less than 50% English at home ($n = 2$), failing to look at the monitor on the right side ($n = 1$), developmental concerns that arose after participating in the study ($n = 1$), or for falling asleep during the study ($n = 1$).

Task Details

All infants were tested on the VSL task. The task Apparatus, Stimuli, and Procedure are described in detail in Chapter II. Details about the data collection, eye movement coding, and the calculation of the dependent variables are also described in Chapter II.

Coding reliability. A first coder coded eye movements for all of the trials for all of the infants. Then a second coder coded all trials for a randomly-selected 25 percent of the infants (n = 15) for reliability. The second coder was blind to the purpose of the experiment. Coding for anticipatory looks resulted in 90% agreement between the two coders and was discussed until there was 100% agreement. The average correlation between coders on RT prior to discussion was 0.99.

Language Measures

In order to measure the relationship between VSL performance in infancy and English spoken language abilities at later time points, parents were asked to fill out language questionnaires about their child. The MacArthur-Bates Communicative Development Inventories (Fenson et al., 2006) were used—both the 'Words and Gestures' (CDI-1) and the 'Words and Sentences' (CDI-2) form. Detailed descriptions of the two forms can be found in Chapter II.

Results

Three sets of analyses were conducted. First, children's performance on the VSL task was analyzed to determine whether they learned the spatiotemporal sequence (see Table 4-1 for VSL task descriptive statistics). Second, correlation analyses were conducted between children's performance on the VSL task and their concurrent CDI ability. Third, correlation analyses were conducted between children's performance on the VSL task and their later CDI ability—as reported at approximately 13.5, 17.5, 23.5, and 28.5 months of age (see Tables 4-2 and 4-3 for CDI descriptive statistics). Due to the number of significance tests performed, an α level of .01 was used.

Did Infants Learn the Sequence?

In order to answer this question 2 paired-samples t tests were conducted: one on the change in RT from Phase 1 to Phase 2 [$t(54) = 1.96, p = .055, d = -.26, CI_{.95} = -.64$ to $.11$] and one on the change in the number of correct anticipatory looks from Phase 1 to Phase 2 [$t(54) = 1.05, p = .298, d = -.14, CI_{.95} = -.51$ to $.23$; see Table 4-1 for descriptive statistics]. Contrary to our prediction, there was an increase in RT from Phase 1 to Phase 2 instead of a decrease. There was the predicted increase in correct anticipatory looks, but it was not significant. This suggests that as a group, the 8.5-month-old infants may not have learned the visual sequence.

The raw increase in anticipatory looks (i.e., getting faster) seems contradictory to the group increase in RT (i.e., getting slower). The reason for this is that not all of the infants had anticipatory looks. In Phase 1 there were 12 infants who had no anticipatory looks and 15 infants who had only 1 anticipatory look. In Phase 2 there were 10 infants who had no anticipatory looks and 10 who had only 1 anticipatory look. This means that only a subset of the infants were included in the anticipatory looks analysis, while all infants were included in the measure of RT. This means that there were fewer infants who demonstrated learning (i.e., a speeding up of RT) compared to those who did not. However, of the 26 infants who showed an increase in anticipatory looks in Phase 2, the majority of them (16) also demonstrated an overall decrease in RT.

The fact that the group overall did not demonstrate learning the sequence, and even increased their latencies, suggests that the task may have been difficult for infants this age. Indeed, only 22 of the 55 infants showed the expected RT pattern (a decrease in RT from Phase 1 to Phase 2) and only 26 had an increase in correct anticipatory looks

Table 4-1

Descriptive Statistics for VSL Task Measures

Measure	Median RT in Phase 1 (sec)	Median RT in Phase 2 (sec)	Correct Anticipatory Looks in Phase 1	Correct Anticipatory Looks in Phase 2
M	0.49	0.58	1.87	2.16
SD	0.27	0.36	1.53	1.56
Range	0.07 - 1.30	0 - 1.73	0 - 5	0 - 6

Table 4-2

Descriptive Statistics for CDI-1Measures at 8.5 (n = 53) and 13.5 (n = 38) Months of Age

Measure	8.5mo Vocab Comprehension	8.5mo Gestures	13.5mo Vocab Comprehension	13.5mo Gestures	13.5mo Vocab Production
Using Raw Scores					
M	32.62	11.32	92.76	28.26	10.50
SD	31.22	6.54	75.97	8.54	8.29
Range	0 - 138	0 - 34	0 - 396	14 - 50	0 - 32
Using Corrected Scores (i.e., total vocabulary)					
M	-	-	-	-	11.24
SD	-	-	-	-	9.31
Range	-	-	-	-	0 - 36

Table 4-3

Descriptive Statistics for CDI-2Measures at 17.5 (n = 36), 23.5 (n = 39), and 28.5 (n = 27) Months of Age

Measure	17.5mo Vocab Production	23.5mo Vocab Production	23.5mo Inflection	23.5mo Irregulars	23.5mo Over-Regulars[1]	28.5mo Vocab Production	28.5mo Inflection	28.5mo Irregulars	28.5mo Over-Regulars[2]
Using Raw Scores									
M	59.28	247.23	2.82	3.18	0.31	437.54	5.50	7.61	0.61
SD	54.60	143.07	2.60	3.72	0.47	156.75	2.53	6.11	0.50
Range	3 - 258	20 - 525	0 - 8	0 - 15	0 or 1	172 - 653	0 - 8	0 - 21	0 or 1
Using Corrected Scores (i.e., total vocabulary)									
M	73.11	424.82	-	-	-	997.57	-	-	-
SD	80.37	327.05	-	-	-	565.31	-	-	-
Range	3 - 394	21 - 1186	-	-	-	233 - 2124	-	-	-

[1]12 infants were reported to over-regularize nouns/verbs at 23.5 months; [2]16 infants were reported to over-regularize nouns/verbs at 28.5 months

from Phase 1 to 2. It is possible that there were two distinct groups of infants—'learners' whose RTs *decreased* as they learned the sequence and 'non-learners' who did not pick up on the pattern and got bored, thus showing the unexpected pattern of *increased* latencies across the session. To evaluate this possibility the data for the learners and the non-learners were separated and analyzed separately in the following sections.

Although the expectation was that the group as a whole would show a decrease in RT from Phase 1 to Phase 2, the main focus of this study was to investigate the relationship between RT change and reported language (CDI) ability. Thus the key finding here is that there was a lot of variability in infants' performance, with some infants demonstrating clear patterns of learning.

Does VSL Task Performance Correlate with Infants' Receptive Language Ability?

In order to answer this question correlation analyses were conducted between RT difference scores and scores on the 8.5 month CDI-1 from the study visit for the 53 infants whose parents completed a CDI-1 (age range at CDI-1 was 8.0 – 11.3 months old, M = 8.7 months). The RT difference score is Phase 1 RT minus Phase 2 RT, so a positive difference score indicates a decrease in RT, or learning of the sequence.

Analyses relied on raw CDI-1 scores (controlling for age at CDI-1) due to the lack of variability in CDI percentile scores for children this age. The RT difference score was positively correlated with Vocabulary Comprehension ($r = .35$, $p = .006$, $z_r = .37$, $CI_{.95} =$ .09 to .64; see Figure 4-1), but not significantly correlated with Gesture Comprehension ($r = .12$, $p = .195$, $z_r = .12$, $CI_{.95} = -.16$ to .40; see Figure 4-2). Specifically, infants whose RTs decreased from Phase 1 to Phase 2 had higher receptive vocabulary ability. This suggests that infants' success at learning the spatiotemporal sequence was positively related to their concurrent vocabulary comprehension ability at 8.5 months of age (see Table 4-4). Correlations were also computed between CDI-1 scores and the increase in anticipatory looks from Phase 1 to Phase 2. None of those correlations was significant after controlling for Type-I error inflation ($\alpha = .01$).

Next the learners ($n = 22$) and the non-learners ($n = 31$) were examined. There was a significant difference in 8.5 month Vocabulary Comprehension ability [$t(51) = 2.89$, $p = .006$, $d = .78$, $CI_{.95} = 0.22$ to 1.35], with learners demonstrating greater vocabulary comprehension ability (M = 46.41 words out of a possible 396, SD = 40.58) than the non- learners (M = 22.84 words, SD = 17.28). In order to further understand the differences between the learners and non-learners, correlation analyses between VSL performance (RT difference score) and raw CDI-1 scores (controlling for age at CDI-1) were conducted on each group separately. Weak or no correlations among the CDI-1 scores and VSL performance for the non-learners were expected because if these infants simply did not learn the sequence then the changes in their latencies are likely to be determined by other factors (e.g., fatigue) and thus should not be associated with vocabulary scores. In other words, the expectation was that there would logically not be degrees of non- learning that would be meaningfully related to vocabulary development. On the other hand, there likely exist degrees of learning that are meaningful: the better and faster an infant learns the sequence, the greater the decrease in latency, and as predicted, the better their vocabulary ability. Thus, stronger correlations among the CDI-1 scores and VSL performance were expected for the learners than for the non-learners. The results of the correlation analyses were consistent with these predictions (see Table 4-5). The learners' RT difference score correlated positively with vocabulary comprehension whereas the non-learners' RT difference score did not, confirming the existence of two subgroups: one that learned the sequence to varying degrees and another group that simply showed no learning.

Does VSL Task Performance Correlate with Infants' Receptive Language Ability 5 Months after Participating in the Study?

In order to answer this question correlation analyses were conducted between the RT difference score and the CDI-1 scores from the follow-up CDI-1 that was mailed to parents approximately 5 months after their lab visit. Not all of the parents returned the follow-up CDI-1, so these analyses were conducted for only a subset of the sample (38 infants, age range 12.7 – 14.4 months old, M = 13.3 months). Using raw CDI-1 scores (controlling for age at CDI-1), the RT difference score was not significantly correlated with Vocabulary Production ($r = -.08$, $p = .329$, $z_r = -.08$, $CI_{.95} = -.41$ to .25). However, the RT difference score was marginally correlated with Gesture Comprehension ($r = .30$, $p = .038$, $z_r = .31$, $CI_{.95} = -.02$ to .64) and was significantly correlated with Vocabulary Comprehension ($r = .39$, $p = .009$, $z_r = .41$, $CI_{.95} = .08$ to .74). This suggests that infants' success at learning the spatiotemporal sequence was positively related to their vocabulary comprehension ability at 13.5 months of age (see Table 4-6). In addition, although there may be a lack of statistical power, the correlation value with Gesture Comprehension is in the predicted direction—a decrease in RT from Phase 1 to Phase 2 is associated with higher receptive language ability. Correlations were also calculated between CDI-1 scores and the increase in anticipatory looks from Phase 1 to Phase 2. None of those correlations were significant (see Table 4-6).

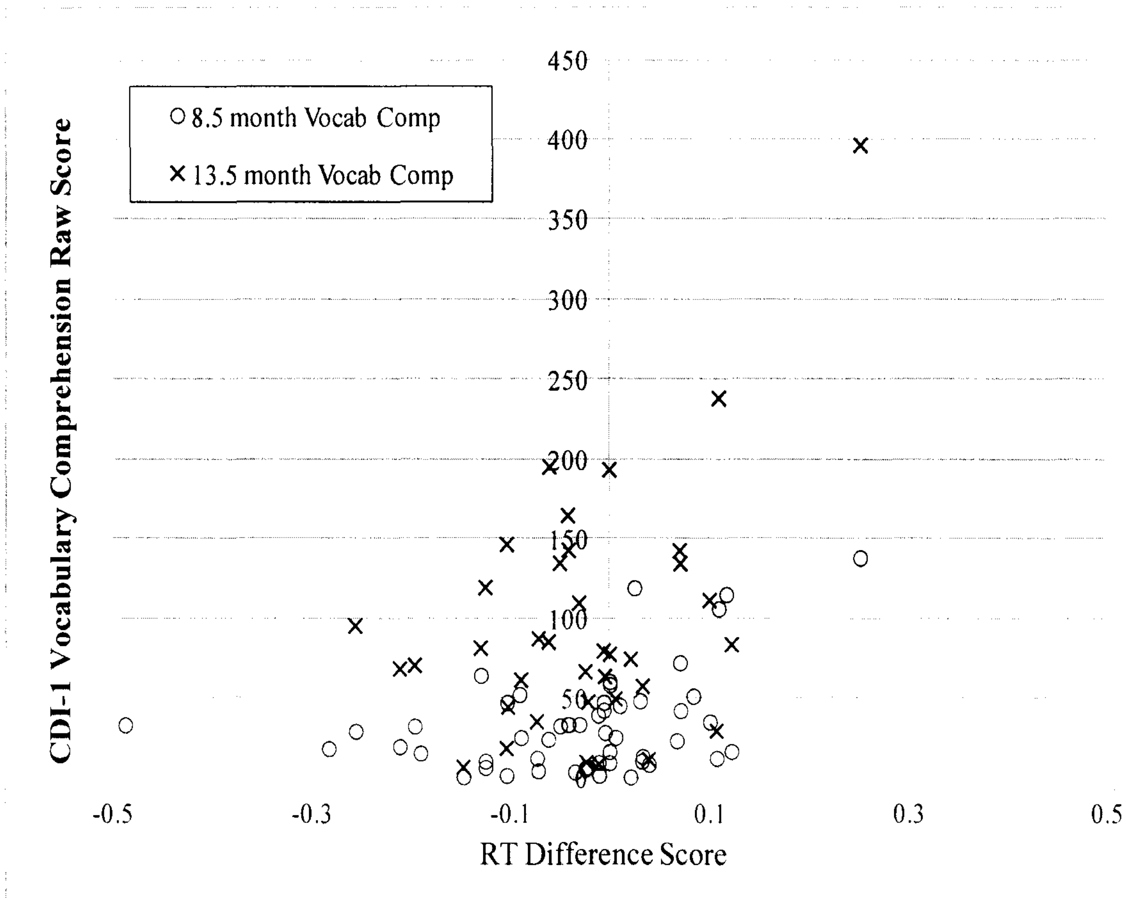

Figure 4-1. Scatterplots for CDI-1 Vocabulary Comprehension scores at 8.5 months and 13.5 months, with the RT difference score.

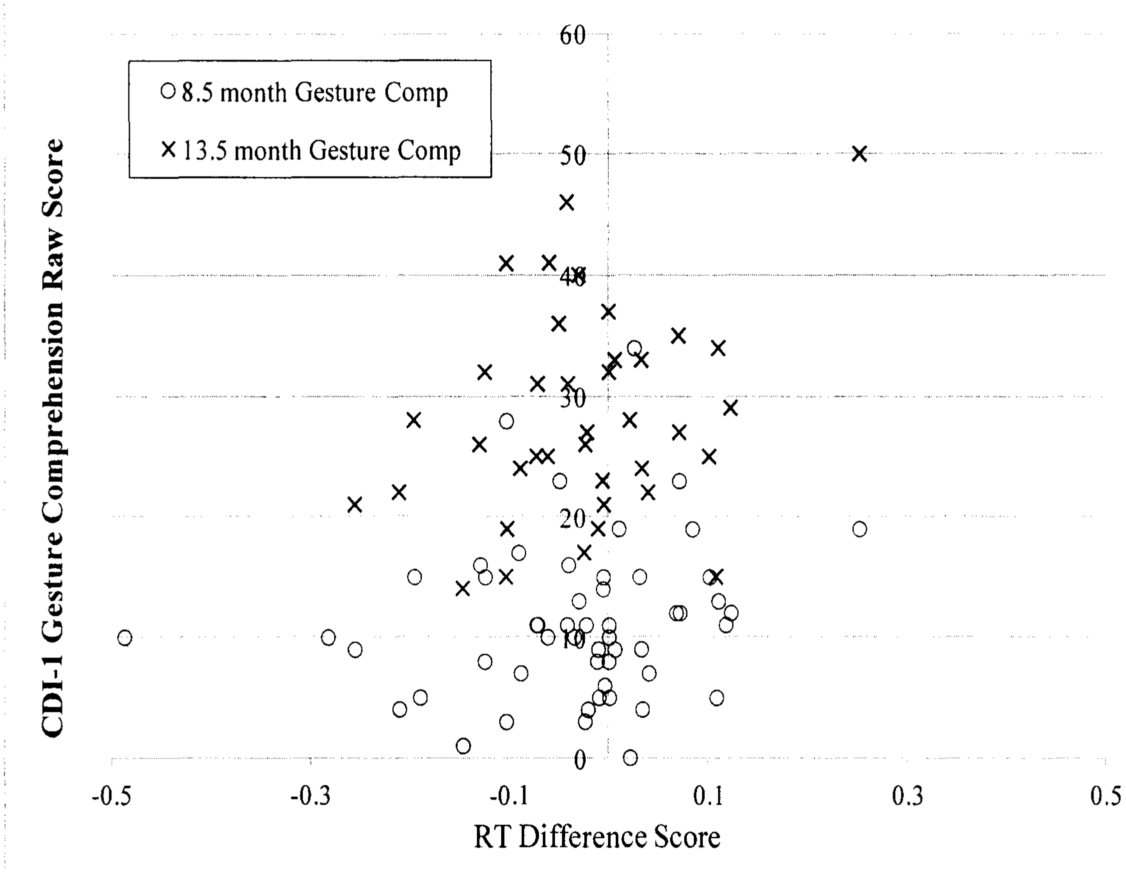

Figure 4-2. Scatterplots for CDI-1 Gesture Comprehension scores at 8.5 months and 13.5 months, with the RT difference score.

Table 4-4

Partial Correlations between VSL Performance and CDI-1 Measures at 8.5 Months (Controlling for Age at CDI)

Measure	1	2	3	4
1. Proportion of change in RT Phase 1 to Phase 2	---			
p value (one-tailed)	---			
2. Change in Anticipatory looks from Phase 1 to Phase 2	.42*	---		
p value (one-tailed)	*.001*			
3. Vocab Comprehension (8.5 months)	.35*	.26	---	
p value (one-tailed)	*.006*	*.034*		
4. Gestures (8.5 months)	.12	.05	.59*	---
p value (one-tailed)	*.195*	*.355*	*<.001*	---

Table 4-5

Partial Correlations between VSL Performance and CDI-1 Measures at 8.5 Months by Learner Status (Controlling for Age at CDI)

Measure	Proportion of change in RT Phase 1 to Phase 2	Change in Anticipatory looks from Phase 1 to Phase 2	Vocab Comprehension (8.5 months)	Gestures (8.5 months)
'Learners' (*n* = 19)				
Vocab Comprehension (8.5 months)	.54*	.02	---	
p value (one-tailed)	*.006*	*.471*	---	
Gestures (8.5 months)	.33	.06	0.68*	---
p value (one-tailed)	*.072*	*.396*	*<.001*	---
'Non-Learners' (*n* = 28)				
Vocab Comprehension (8.5 months)	-.09	.24	---	
p value (one-tailed)	*.317*	*.105*	---	
Gestures (8.5 months)	.04	.02	.58*	---
p value (one-tailed)	*.414*	*.455*	*<.001*	---

Table 4-6

Partial Correlations between VSL Performance and CDI-1 Measures at 13.5 Months (Controlling for age at CDI)

Measure	1	2	3	4	5
1. Proportion of change in RT Phase 1 to Phase 2	---				
p value (one-tailed)	---				
2. Change in Anticipatory looks from Phase 1 to Phase 2	.44*	---			
p value (one-tailed)	*.003*	---			
3. Vocab Comprehension (13.5 months)	.39*	.16	---		
p value (one-tailed)	*.009*	*.180*	---		
4. Gesture Comprehension (13.5 months)	.30	.19	.74*	---	
p value (one-tailed)	*.038*	*.136*	*<.001*	---	
5. Vocab Production (13.5 months)[1]	-.06	.18	.43*	.55*	---
p value (one-tailed)	*.367*	*.144*	*.004*	*<.001*	---

[1]The corrected total vocabulary score was used, so age at CDI was not partialled out

Table 4-7

Partial Correlations between VSL Performance and CDI-1 Measures at 13.5 Months by Learner Status (Controlling for Age at CDI)

Measure	Proportion of change in RT Phase 1 to Phase 2	Change in Anticipatory looks from Phase 1 to Phase 2	Vocab Comprehension (13.5 months)	Gesture Comprehension (13.5 months)	Vocab Production (13.5 months)
'Learners' (n = 14)					
Vocab Comprehension (13.5 months)	.67*	.02	---		
p value (one-tailed)	*.006*	*.480*	---		
Gesture Comprehension (13.5 months)	.33	.09	.76*	---	
p value (one-tailed)	*.134*	*.390*	*.001*	---	
Vocab Production (13.5 months)[1]	-.18	.39	.27	.23	---
p value (one-tailed)	*.266*	*.085*	*.180*	*.219*	---
'Non-Learners' (n = 24)					
Vocab Comprehension (13.5 months)	.06	.07	---		
p value (one-tailed)	*.395*	*.382*	---		
Gesture Comprehension (13.5 months)	.23	.13	.83*	---	
p value (one-tailed)	*.141*	*.279*	*<.001*	---	
Vocab Production (13.5 months)[1]	-.21	.06	.65*	.70*	---
p value (one-tailed)	*.157*	*.393*	*<.001*	*<.001*	---

[1]The corrected total vocabulary score was used, so age at CDI was not partialled out

Table 4-8

Correlations between VSL Performance and CDI-2 Vocabulary Production at 17.5 (n = 36), 23.5 (n = 39), and 28.5 (n = 27) Months

Measure	1	2	3	4	5
1. Proportion of change in RT Phase 1 to Phase 2	---				
p value (one-tailed)	---				
2. Change in Anticipatory looks from Phase 1 to Phase 2	.42*	---			
p value (one-tailed)	*.001*	---			
3. Vocab Production (17.5 months)	-.08	-.03	---		
p value (one-tailed)	*.315*	*.431*	---		
4. Vocab Production (23.5 months)	-.15	.14	.73*	---	
p value (one-tailed)	*.179*	*.191*	*<.001*	---	
5. Vocab Production (28.5 months)	-.15	.27	.61*	.86*	---
p value (one-tailed)	*.222*	*.085*	*.001*	*<.001*	---

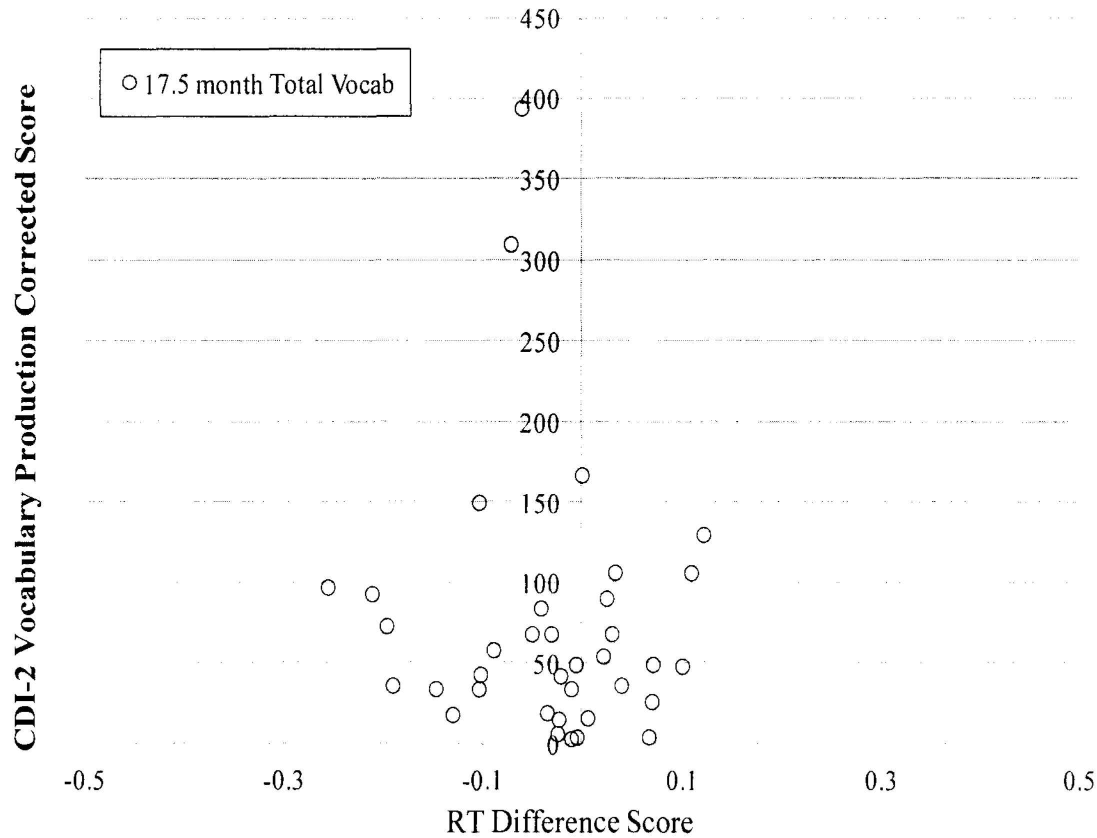

Figure 4-3. Scatterplot for CDI-2 Corrected Vocabulary Production score at 17.5 months, with the RT difference score.

Again potential differences between infants who demonstrated learning of the sequence (n = 14) and those who did not (n = 24) were investigated. Contrary to results from the 8.5 month CDI-1, there was a nonsignificant difference in 13.5 month vocabulary comprehension ability for learners and non-learners [$t(36) = 1.32, p = .195, d = .43, CI_{95} = -0.24$ to 1.09], although the learners did have greater reported vocabulary comprehension ability (M = 113.86 words out of a possible 396, SD = 105.45) than the non-learners (M = 80.46 words, SD = 50.69). Correlation analyses were conducted between the RT difference score and raw CDI-1 scores (controlling for age at CDI-1) on each group separately. Again, weak or no correlations among the CDI-1 scores and VSL performance for the non-learners were expected and positive correlations were expected for the learners. As with the 8.5 month CDI-1, the learners' RT difference score was significantly positively correlated with 13.5 month Vocabulary Comprehension whereas the non-learners' RT difference score was not (see Table 4-7).

Does VSL Task Performance Correlate with Infants' Productive Vocabulary 9 Months after Participating in the Study?

In order to answer this question correlation analyses were conducted between the RT difference score and the CDI-2 scores from the follow-up CDI-2 that was mailed to parents approximately 9 months after their lab visit. These analyses were conducted for the subset of the sample whose parents returned the follow-up CDI-2 (36 infants, age range 17.0 – 19.3 months old, M = 17.6 months). Using corrected CDI-2 scores, the RT difference score was not significantly correlated with vocabulary production at approximately 17.5 months old ($r = -.08, p = .315, z_r = -.08, CI_{95} = -.42$ to .26; see Figure 4-3 and Table 4-8). This is a different pattern than the previous analyses on the CDI-1 comprehension abilities, but importantly, this is the first analysis investigating a relation between VSL task performance and language *production*. Some potential explanations for these divergent results are presented in the Discussion section.

Does VSL Task Performance Correlate with Infants' Productive Language Ability 15 Months after Participating in the Study?

In order to answer this question correlation analyses were conducted between the RT difference score and the CDI-2 scores from the follow-up CDI-2 that was mailed to parents approximately 15 months after their lab visit. Not all of the parents returned the follow-up CDI-2, so these analyses were conducted for 39 infants (age range 22.8–26.3 months old, M = 23.5 months). Using corrected CDI-2 scores, the RT difference score was not significantly correlated with vocabulary production at approximately 23.5 months old (r = -.15, p = .179, z_r = -.15, $CI_{.95}$ = -.48 to .18; see Figure 4-4 and Table 4-8; see Table 4-9 for intercorrelations among vocabulary production and grammatical measures at 23.5 months).

Another focus of the current study was how performance on the VSL task correlated with grammatical ability. Specifically, the hypothesis was that sequence learning (thought to rely on procedural memory) may contribute to grammar acquisition (see Kidd, 2012; Ullman, 2004). This possibility was tested via correlation analyses between VSL task performance at 8.5 months of age to reported CDI-2 grammatical ability at 23.5 months. The correlations between RT difference score and Over-Regulars, Irregulars, and Inflection were all nonsignificant (see Figure 4-5, Figure 4-6, & Table 4-10). This suggests that as a group, the infants' performance on the VSL task at 8.5 months was not related to reported English grammatical ability at approximately 23.5

months. However, just under half of the children had demonstrated learning the sequence, which could have a significant effect on the correlation analyses. Therefore, as was done with the analyses on the CDI-1, correlation patterns for the learners (n = 15) compared to the non-learners (n = 24) were explored to look for different patterns. The same correlation analyses were conducted separately for the two learner groups and there were significant negative correlations between the RT difference score and Irregulars (r = -.61, p = .007, z_r = -.71, $CI_{.95}$ = -1.27 to -.14) and Over-Regulars (r = -.60, p = .009, z_r = -.69, $CI_{.95}$ = -1.26 to -.13) for children who had demonstrated learning of the visual sequence at 8.5 months of age, but no significant correlations for the non-learners (see Table 4-11). This pattern suggests that infants whose RTs decreased over the course of the study at 8.5 months old (i.e., the learners) tended to use fewer irregular nouns/verbs and to not over-regularize nouns/verbs at 23.5 months old. These results also suggest that, for infants who did not demonstrate learning, VSL performance in infancy is not significantly related to grammatical ability 15 months later.

Does VSL Task Performance Correlate with Infants' Productive Language Ability 20 Months after Participating in the Study?

In order to answer this question correlation analyses were conducted between the RT difference score and the CDI-2 scores from the follow-up CDI-2 that was mailed to parents approximately 20 months after their lab visit. Parents of 28 of the infants returned the follow-up CDI-2 (age range 27.8–31.0 months old, M = 28.5 months). Using corrected CDI-2 scores, the RT difference score was not significantly correlated with vocabulary production at approximately 28.5 months old (r = -.15, p = .222, z_r = -.15,

$CI_{.95}$ = -.55 to .25; see Figure 4-4 and Table 4-8; see Table 4-9 for intercorrelations among vocabulary production and grammatical measures at 28.5 months).

Whether or not performance on the VSL task was correlated with grammatical ability was also of interest. This possibility was tested via correlation analyses between VSL task performance at 8.5 months of age to reported CDI-2 grammatical ability at 28.5 months. The correlations between RT difference score and Over-Regulars was significant (r = -.49, p = .004, z_r = -.54, $CI_{.95}$ = -.94 to -.14; see Table 4-12). The correlations between RT difference score and the other grammar measures were both marginally significant (Inflection r = -.26, p = .095, z_r = -.27, $CI_{.95}$ = -.67 to .09; Irregulars r = -.39, p = .021, z_r = -.40, $CI_{.95}$ = -.80 to .00; see Figures 4-5 and 4-6). Interestingly, all of the correlations were negative, suggesting that children whose RTs decreased over the course of the study at 8.5 months old produced fewer irregular nouns/verbs, used less regular inflection, and did not over-regularize nouns/verbs at 28.5 months.

In order to further investigate this peculiar pattern, the same correlation analyses were conducted separately for the two learner groups. There was a marginal negative correlation between the RT difference score and Over-Regulars for children who had demonstrated learning of the visual sequence at 8.5 months of age (n = 10) (r = -.75, p = .006, z_r = -.97, $CI_{.95}$ = -1.77 to -.17), but nonsignificant correlations for the Inflection measure and Irregulars (see Table 4-13). In the non-learners (n = 18) there was a significant negative correlation between the RT difference score and Inflection (r = -.58, p = .006, z_r = -.66, $CI_{.95}$ = -1.17 to -.16) and marginally significant negative correlations with Irregulars and Over-Regulars (r = -.45, p = .03, z_r = -.48, $CI_{.95}$ = -.99 to .02; r = -.33,

$p = .093$, $z_r = -.34$, $CI_{.95} = -.85$ to $.16$, respectively). This suggests that infants who did not demonstrate learning of the visual sequence at 8.5 months were more likely to use regular inflection, produce irregular nouns/verbs, and to over-regularize nouns/verbs at approximately 28.5 months of age. However, as shown in the scatterplots (Figures 4-5 and 4-6), there is a lot of variability in the relationship between VSL task performance and the CDI-2 grammatical measures. Therefore these negative correlations (although significant) are difficult to interpret.

Discussion

In the current investigation of visual sequence learning (VSL) and its connection to language development in infants, receptive language measures were collected to probe the relation between VSL and language comprehension ability. Contrary to expectations, infants as a group did not demonstrate learning of the spatiotemporal sequence. One explanation for this pattern is that whereas some infants did show sequence learning, others did not, and their latencies actually increased because the task became tiresome for them.

Overall there was a great deal of variability in infants' performance on the VSL task, which seemed to be meaningful: infants whose RTs decreased (i.e., demonstrated learning of the sequence) tended to have higher receptive vocabulary ability at testing and at follow-up at 13.5 months. The non-learners had lower vocabulary comprehension scores than the learners and among the learners, there was a linear relationship between degree of learning and receptive vocabulary. At the later follow-up time points (17.5, 23.5, and 28.5 months), VSL performance was not related to productive vocabulary ability for either the learners or the non-learners, but there were some interesting correlations between VSL performance and grammatical ability for both groups of infants. A discussion of these findings is in the General Discussion (Chapter VII).

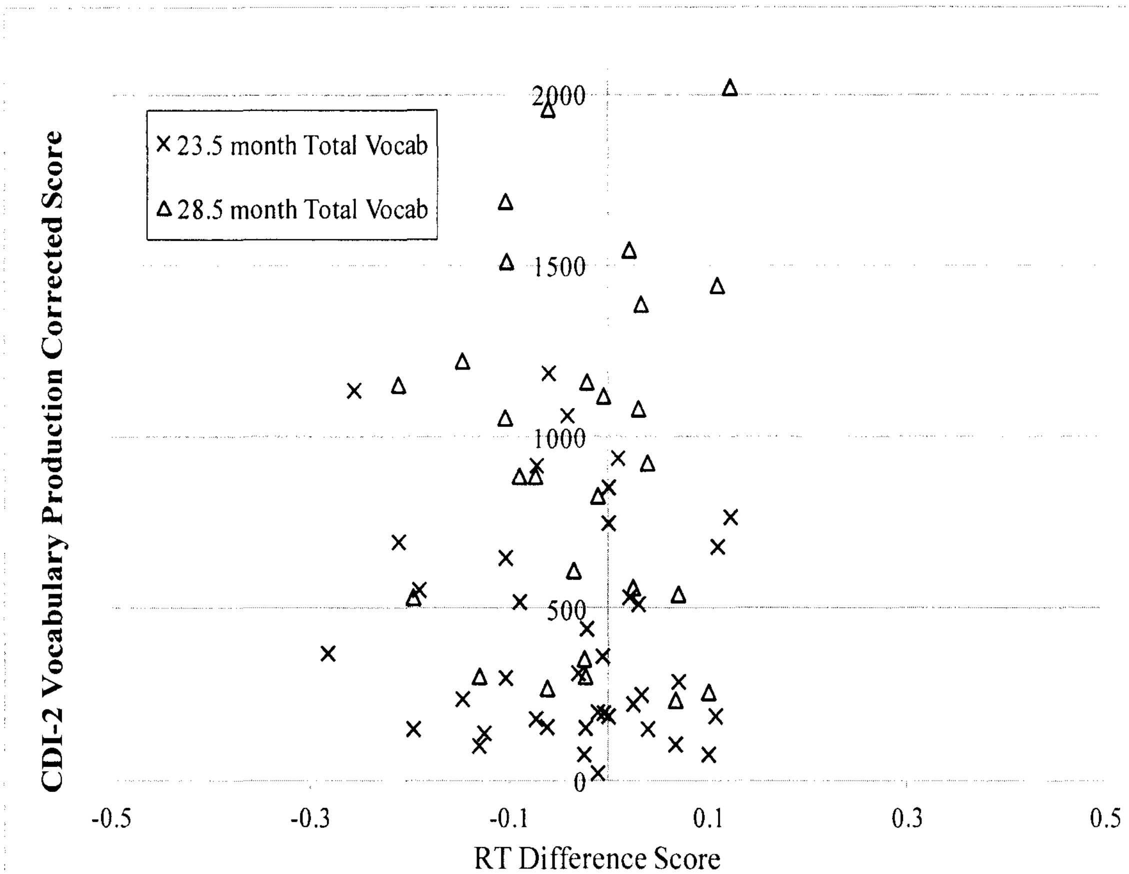

Figure 4-4. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 23.5 months and 28.5 months, with the RT difference score.

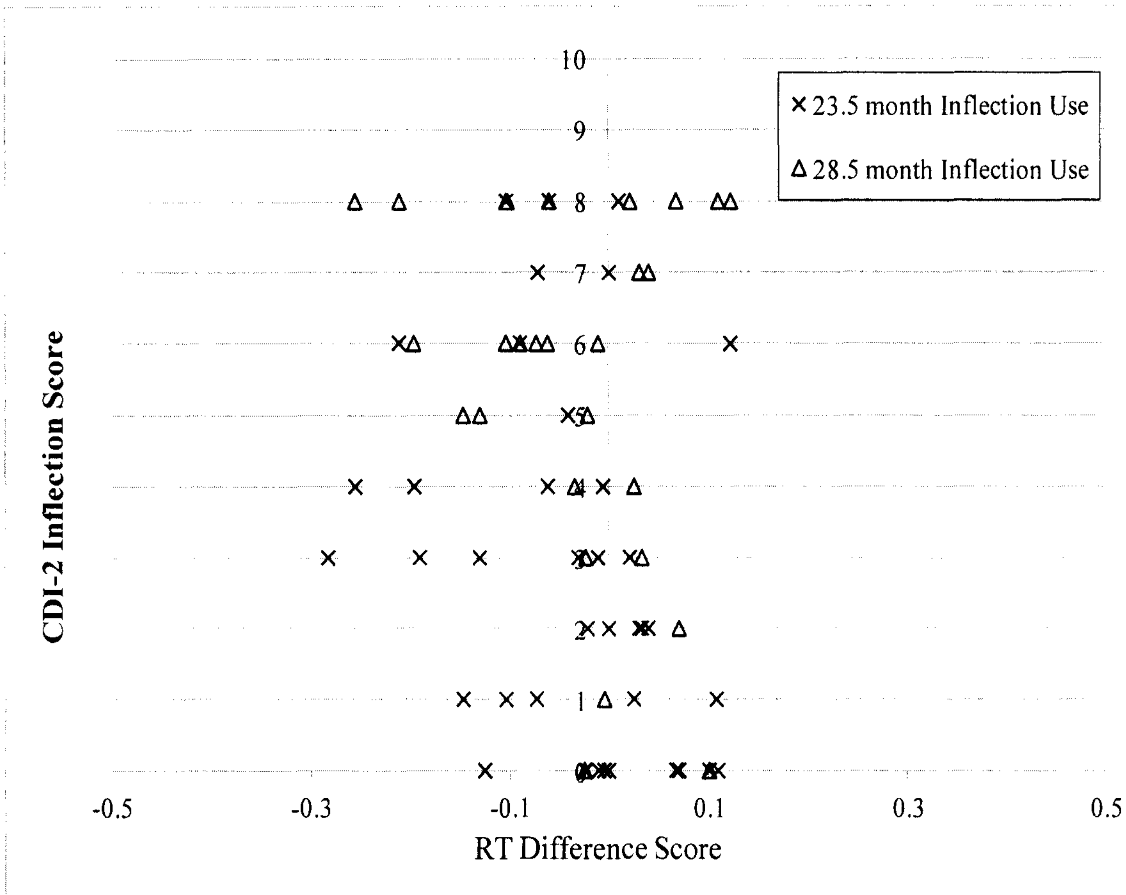

Figure 4-5. Scatterplots for CDI-2 Inflection scores at 23.5 months and 28.5 months, with the RT difference score.

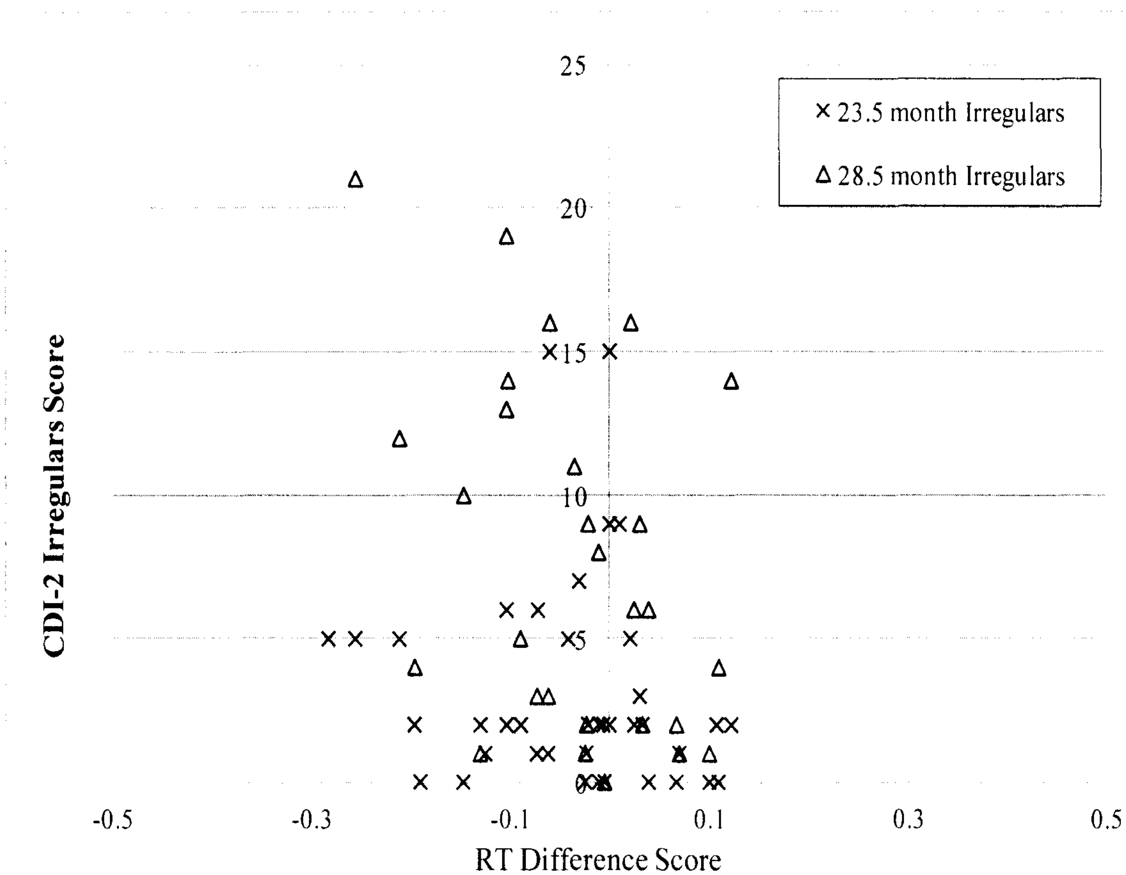

Figure 4-6. Scatterplots for CDI-2 Irregulars scores at 23.5 months and 28.5 months, with the RT difference score.

Table 4-9

Correlations among CDI-2 Vocabulary and Grammatical Measures at 23.5 and 28.5 Months

Measure	1	2	3	4	5	6
1. Vocab Production (23.5 months)	---					
p value (one-tailed)	---					
2. Inflection (23.5 months)	.73	---				
p value (one-tailed)	*<.001*	---				
3. Irregulars (23.5 months)	.71	.62	---			
p value (one-tailed)	*<.001*	*<.001*	---			
4. Vocab Production (28.5 months)	.85	.54	.58	---		
p value (one-tailed)	*<.001*	*.002*	*.001*	---		
5. Inflection (28.5 months)	.60	.60	.46	.57	---	
p value (one-tailed)	*.001*	*.001*	*.010*	*.001*	---	
6. Irregulars (28.5 months)	.79	.65	.66	.78	.66	---
p value (one-tailed)	*<.001*	*<.001*	*<.001*	*<.001*	*<.001*	---

Note: 26 children had CDI-2 data at both 23.5 and 28.5 months; 39 children had CDI-2 data at 23.5 months; 28 children had CDI-2 data at 28.5 months.

Table 4-10

Correlations between VSL Performance and CDI-2 Grammatical Measures at 23.5 Months

Measure	1	2	3	4	5
1. Proportion of change in RT Phase 1 to Phase 2	---				
p value (one-tailed)	---				
2. Change in Anticipatory looks from Phase 1 to Phase 2	.38*	---			
p value (one-tailed)	*.008*	---			
3. Inflection (23.5 months)	-.27	.009	---		
p value (one-tailed)	*.048*	*.478*	---		
4. Irregulars (23.5 months)	-.12	.127	.62*	---	
p value (one-tailed)	*.230*	*.221*	*<.001*	---	
5. Over-Regulars (23.5 months)	-.073	.292	.24	.54*	---
p value (one-tailed)	*.329*	*.035*	*.069*	*<.001*	---

Table 4-11

Correlations between VSL Performance and CDI-2 Grammatical Measures at 23.5 Months by Learner Status

Measure	Proportion of change in RT Phase 1 to Phase 2	Change in Anticipatory looks from Phase 1 to Phase 2	Inflection (23.5 months)	Irregulars (23.5 months)	Over-Regulars (23.5 months)
'Learners' (*n* = 15)					
Inflection (23.5 months)	-.28	-.20	---		
p value (one-tailed)	*.156*	*.240*	---		
Irregulars (23.5 months)	-.61*	-.132	.55	---	
p value (one-tailed)	*.007*	*.320*	*.017*	---	
Over-Regulars (23.5 months)	-.60*	.09	.29	.56	---
p value (one-tailed)	*.009*	*.377*	*.151*	*.015*	---
'Non-Learners' (*n* = 24)					
Inflection (23.5 months)	-.21	.26	---		
p value (one-tailed)	*.166*	*.115*	---		
Irregulars (23.5 months)	-.11	.26	.73*	---	
p value (one-tailed)	*.306*	*.114*	*<.001*	---	
Over-Regulars (23.5 months)	-.17	.34	.27	.52*	---
p value (one-tailed)	*.216*	*.052*	*.101*	*.004*	---

Table 4-12

Correlations between VSL Performance and CDI-2 Grammatical Measures at 28.5 Months

Measure	1	2	3	4	5
1. Proportion of change in RT Phase 1 to Phase 2	---				
p value (one-tailed)	---				
2. Change in Anticipatory looks from Phase 1 to Phase 2	.42*	---			
p value (one-tailed)	*.001*	---			
3. Inflection (28.5 months)	-.26	.33	---		
p value (one-tailed)	*.095*	*.042*	---		
4. Irregulars (28.5 months)	-.39	.15	.66*	---	
p value (one-tailed)	*.021*	*.218*	*<.001*	---	
5. Over-Regulars (28.5 months)	-.49*	-.15	.49*	.53*	---
p value (one-tailed)	*.004*	*.213*	*.004*	*.002*	---

Table 4-13

Correlations between VSL Performance and CDI-2 Grammatical Measures at 28.5 Months by Learner Status

Measure	Proportion of change in RT Phase 1 to Phase 2	Change in Anticipatory looks from Phase 1 to Phase 2	Inflection (28.5 months)	Irregulars (28.5 months)	Over-Regulars (28.5 months)
'Learners' (n = 9)					
Inflection (28.5 months)	-.01	.16	---		
p value (one-tailed)	*.485*	*.327*	---		
Irregulars (28.5 months)	-.14	-.18	.62	---	
p value (one-tailed)	*.347*	*.314*	*.028*	---	
Over-Regulars (28.5 months)	-.75	-.63	.29	.51	---
p value (one-tailed)	*.006*	*.026*	*.210*	*.068*	---
'Non-Learners' (n = 18)					
Inflection (28.5 months)	-.58*	.53	---		
p value (one-tailed)	*.006*	*.013*	---		
Irregulars (28.5 months)	-.45	.47	.72*	---	
p value (one-tailed)	*.030*	*.025*	*<.001*	---	
Over-Regulars (28.5 months)	-.33	.32	.68*	.52	---
p value (one-tailed)	*.093*	*.095*	*.001*	*.014*	---

CHAPTER V

CORRELATIONS BETWEEN VISUAL RECOGNITION MEMORY AND LANGUAGE DEVELOPMENT IN NORMAL-HEARING INFANTS

This chapter attempts to confirm the link between visual recognition memory in infancy and spoken language outcomes up to age 30 months for infants with normal hearing.

The current study presents an investigation of the relation between early language development and performance on a visual recognition memory (VRM) task (see Chapter II) as a test of domain-generality in language acquisition. Correlations were estimated between infants' performance on the VRM task and reported MacArthur-Bates Communicative Development Inventory (CDI) vocabulary and grammatical measures (Fenson et al., 2006) at later ages (up to 30 months old) for a group of normal-hearing infants, aged approximately 8.5 months old. It was expected that the current study would replicate previous research by finding a positive correlation between visual recognition memory at approximately 8.5 months old and English productive vocabulary as a toddler. A pattern of results in which performance on the VRM task does not relate to CDI vocabulary would suggest that either the VRM task we designed for the current study does not measure recognition memory in the same manner as in previous studies or that the predictive nature of the relationship is not robust enough to present with only a moderate sample size.

Method

Participants

The participants were 54 infants (31 female). On the day of testing infants ranged in age from 7.9 to 9.8 months ($M = 8.6$, $SD = 0.47$ months) and all had passed their newborn hearing screening. An additional 19 infants (9 female) were tested, but were excluded from analyses for crying/fussing ($n = 12$), being exposed to less than 50% English at home ($n = 2$), experimenter error ($n = 3$), the parent standing up such that the infant was off-camera ($n = 1$), or developmental concerns that arose after participating in the study ($n = 1$).

Task Details

All infants were tested on the VRM task. The task Apparatus, Stimuli, and Procedure are described in detail in Chapter II. Details about the data collection, eye movement coding, and the calculation of the dependent variables are also described in Chapter II.

Coding reliability. A first coder coded eye movements for all of the trials for all of the infants. Then a second coder coded all trials for a randomly-selected 25 percent of the infants ($n = 15$) for reliability. The second coder was blind to the purpose of the experiment. The correlations between coders on looking time ranged from 0.926 to 0.998 with an average correlation of 0.98.

VRM Analyses

On the VRM task, success is defined as recognizing the familiarized images, as indicated by longer looking times to the novel images in the paired–comparison trials. The primary dependent variable was the time spent looking at the target image (the novel one), as a proportion of the total time looking (target + non-target; i.e., novel + familiar) during the trial, which was then multiplied by 100 to be a percentage (hereafter, the novelty score; see Rose et al., 2001). A novelty score was calculated for each test trial (there were a total of 5). Then an average novelty score was calculated for the span-2 test phase, which was an average of the two span-2 test trials, and a separate novelty score was calculated for the span-3 test phase, which was an average of the three span-3 test trials.

Language Measures

In order to measure the relationship between VRM task performance in infancy and English spoken language abilities at later time points, parents were asked to fill out language questionnaires about their child. The MacArthur-Bates 'Words and Gestures' (CDI-1) and the 'Words and Sentences' (CDI-2) forms were used. Detailed descriptions of the two forms can be found in Chapter II.

Results

Three sets of analyses were conducted. First, children's performance on the VRM task was analyzed to determine whether they remembered the familiarized stimuli (see Table 5-1 for VRM task descriptive statistics). Second, correlation analyses were estimated between children's performance on the VRM task and their concurrent CDI ability. Third, correlation analyses were conducted between children's performance on the VRM task and their later CDI ability—as reported at approximately 13.5, 17.5, 23.5, and 28.5 months of age (see Tables 5-2 and 5-3 for CDI descriptive statistics).

Did Infants Demonstrate Recognition Memory for the Stimuli?

One-sample *t* tests, comparing novelty scores to chance performance (50%), were used to address this question. The expectation was that, for each test trial, infants who remembered the familiarized images would have a novelty score significantly above chance. These analyses were first conducted on the pre-test trials. Those trials represented a much easier test of recognition memory because infants only had to remember the previous image (without the interference of intermixed images, as in the span-2 and span-3 phases). On the first pre-test trial infants demonstrated a significant novelty preference [$t(53) = 3.42, p = .001, d = .60, CI_{95} = .21$ to $.98$], but on the second pre-test trial they did not [$t(53) = 0.19, p = .847, d = .03, CI_{95} = -.34$ to $.41$]. The fact that the infants did not demonstrate recognition memory on both of the pre-test trials suggests that either there was proactive interference from the first trial to the second trial, or that the task might not have been age-appropriate. This issue is revisited in the Discussion.

The same analyses were conducted on the test trials, comparing the novelty scores to a chance value of 50%. In the span-2 test phase infants did not demonstrate a significant novelty preference on either of the test trials [$t(53) = 1.51, p = .136, d = .27, CI_{95} = -.11$ to $.65$; $t(53) = 0.97, p = .339, d = .18, CI_{95} = -.20$ to $.55$; in chronological order]. The same comparisons were then conducted on the three test trials in the span-3 test phase [$t(53) = 3.93, p < .001, d = .70, CI_{95} = .31$ to 1.09; $t(53) = 0.35, p = .725, d = .06, CI_{95} = -.31$ to $.44$; $t(53) = 1.72, p = .091, d = .31, CI_{95} = -.07$ to $.69$; in chronological order]. Infants demonstrated a significant novelty preference on the first span-3 test trial and a marginal novelty effect on the third span-3 test trial, but a nonsignificant novelty effect on the span-3 test trial 2. This follows a pattern of recency (trial 3) and primacy (trial 1), which is the kind of pattern one would expect with this kind of memory task. In addition, the fact that the first test trial for each span had a larger effect than the later trials in that span suggests that there may have been proactive interference on the later trials.

When comparing the average novelty scores for the span-2 and span-3 phases to 50%, only the span-3 average novelty score was significantly above chance. This suggests that as a group, the infants remembered the visual stimuli with which they were familiarized only on some of the test trials. This pattern of results is surprising when considering the results of previous studies. In particular, the task in the current study was based on a task used in previous studies (Rose et al., 2001), in which infants demonstrated a consistent novelty preference. Rose and colleagues have been using their VRM task for over 10 years and they have found the task to reliably elicit a novelty preference in pre-term and full-term infants. Notably, some aspects of the task were altered in the current study, and those differences may explain the discrepant findings. This issue is revisited in the Discussion.

Table 5-1

Descriptive Statistics for VRM Task Measures

	Pre-Test Phase		Span-2 Test Phase			Span-3 Test Phase			
Measure	Novelty Score Pre-Test Trial 1	Novelty Score Pre-Test Trial 2	Novelty Score Test Trial 1	Novelty Score Test Trial 2	*Average Span-2 Novelty Score*	Novelty Score Test Trial 1	Novelty Score Test Trial 2	Novelty Score Test Trial 3	*Average Span-3 Novelty Score*
M	58.0%	50.6%	54.8%	53.2%	*54.0%*	60.4%	51.3%	55.8%	*55.8%*
SD	17.3%	23.1%	23.1%	24.7%	*17.9%*	19.4%	26.7%	24.6%	*11.7%*
Range	20.8 - 93.4%	13.2 - 93.3%	0 - 100%	0 - 100%	*0 - 80%*	13.3 - 100%	0 - 100%	0 - 100%	*30.9 - 81.5%*
t (2-tailed *p*)[1]	3.42 (.001)	0.19 (.85)	1.51 (.14)	0.97 (.34)	*1.64 (.11)*	3.93 (<.001)	0.35 (.73)	1.72 (.09)	*3.66 (.001)*

Note: Novelty Score is a percentage, calculated as [looking time to the novel stimulus / (looking time to the novel + looking time to the familiar.

[1]*t*-test is a comparison to chance (50%).

Table 5-2

Descriptive Statistics for the CDI-1 Measures at 8.5 and 13.5 Months

Measure	8.5 mo Vocab Comprehension	8.5 mo Gesture Comprehension	13.5 mo Vocab Comp-rehension	13.5 mo Gesture Comp-rehension	13mo Vocab Production
Using Raw Scores					
n	47	47	38	38	38
M	34.30	10.60	99.76	29.92	11.89
SD	40.28	6.18	91.71	9.64	12.59
Range	0 - 212	0 - 32	0 - 396	14 - 50	0 - 64
Using Corrected Scores (i.e., total vocabulary)					
M	-	-	-	-	13.08
SD	-	-	-	-	15.03
Range	-	-	-	-	0 - 79

Table 5-3

Descriptive Statistics for the CDI-2 Measures at 17.5, 23.5, and 28.5 Months

Measure	17.5 mo Vocab Production	23.5 mo Vocab Production	23.5 mo Inflection	23.5 mo Irregulars	23.5 mo Over-Regulars	28.5 mo Vocab Production	28.5 mo Inflection	28.5 mo Irregulars	28.5 mo Over-Regulars
Using Raw Scores									
n	32	35	35	35	35	29	29	29	29
M	65.03	227.71	2.43	3.17	0.37	440.28	5.45	8.48	0.59
SD	68.68	141.34	2.64	3.92	0.49	178.45	2.80	7.19	0.50
Range	3 - 258	17 - 525	0 - 8	0 - 15	0 or 1	39 - 675	0 - 8	0 - 24	0 or 1
Using Corrected Scores (i.e., total vocabulary)									
M	83.66	382.57	-	-	-	1073.66	-	-	-
SD	103.31	310.41	-	-	-	699.07	-	-	-
Range	3 - 394	18 - 1186	-	-	-	43 - 2742	-	-	-

Does VRM Task Performance Correlate with Infants' Receptive Language Ability?

Even though the infants as a group did not demonstrate robust recognition memory in each test trial, there still might be information to be gleaned from their performance on the VRM task. In particular, Chapter IV describes a study in which there was not a group effect of learning (on the Visual Sequence Learning task), but nonetheless individual differences on that task correlated with language outcomes. Therefore, the next step was to investigate whether a similar pattern might be found in the data for the VRM task. For these and all subsequent correlation analyses three measures from the VRM task were used. The three measures were the overall average novelty score, which was an average across all 5 test trials (span-2 and span-3), the average from span-2, and the average from span-3. The novelty score is the percentage of the total looking time spent looking at the novel stimulus during the trial, so a novelty score greater than 50% indicates a preference for the novel stimulus (i.e., memory for the familiar stimulus). Note that the alpha level was reduced ($\alpha = .01$) in order to control for Type-I error inflation.

Correlation analyses were conducted between novelty scores and scores on the 8.5 month CDI-1 for the 47 infants whose parents completed a CDI-1 at that time (age range at CDI 8.0–10.1 months old, $M = 8.6$, $SD = .46$ months). Using raw CDI-1 scores (controlling for age at CDI-1), the overall average novelty score was not significantly correlated with Vocabulary Comprehension (see Figure 5-1) or Gesture Comprehension (see Figure 5-2 and Table 5-4). Vocabulary Comprehension and Gesture Comprehension were also not significantly correlated with span-2 average or span-3 average novelty scores (see Figures 5-1 and 5-2). This suggests that there was no relationship between infants' preference to look at the novel stimulus (i.e., demonstrated recognition memory for the familiarized stimulus) and their receptive language ability at the time of testing. As expected, Vocabulary Comprehension was significantly correlated with Gesture Comprehension at 8.5 months.

Does VRM Task Performance Correlate with Infants' Receptive Language Ability 5 Months after Participating in the Study?

Correlation analyses between the novelty scores and the CDI-1 scores from the follow-up CDI-1 that was mailed to parents approximately 5 months after their lab visit were used to address this question. Not all of the parents returned the follow-up CDI-1 that was mailed, so these analyses were conducted for only a subset of the sample (38 infants, age range 12.7–14.4 months old, $M = 13.3$, $SD = .42$).

Using raw CDI-1 scores (controlling for age at CDI-1), the overall average novelty score was not significantly correlated with Vocabulary Comprehension (Figure 5-3), but was marginally correlated with Gesture Comprehension (see Figure 5-4 and Table 5-5). Specifically, infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) had poorer gesture comprehension ability 5 months later. Span-2 average and span-3 average novelty scores were not significantly correlated with Vocabulary Comprehension (Figure 5-3), but span-2 average novelty score was negatively correlated with Gesture Comprehension (Figure 5-4). This suggests that infants' success at remembering visual images at 8.5 months old was not strongly correlated with their receptive vocabulary ability, but was negatively related to their gestural ability at approximately 13.5 months of age. As expected, Vocabulary

Comprehension, Gesture Comprehension, and Vocabulary Production were all significantly correlated with each other at 13.5 months.

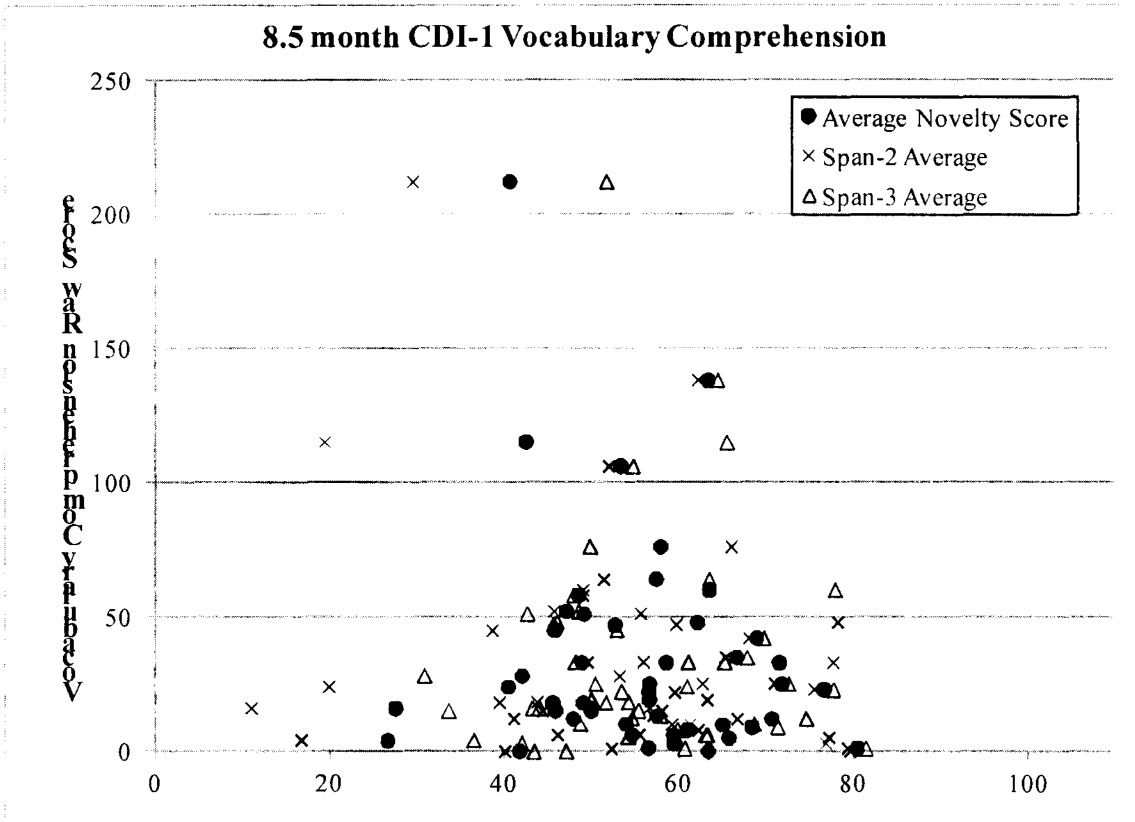

Figure 5-1. Scatterplots for CDI-1 Vocabulary Comprehension scores at 8.5 months and the VRM novelty scores.

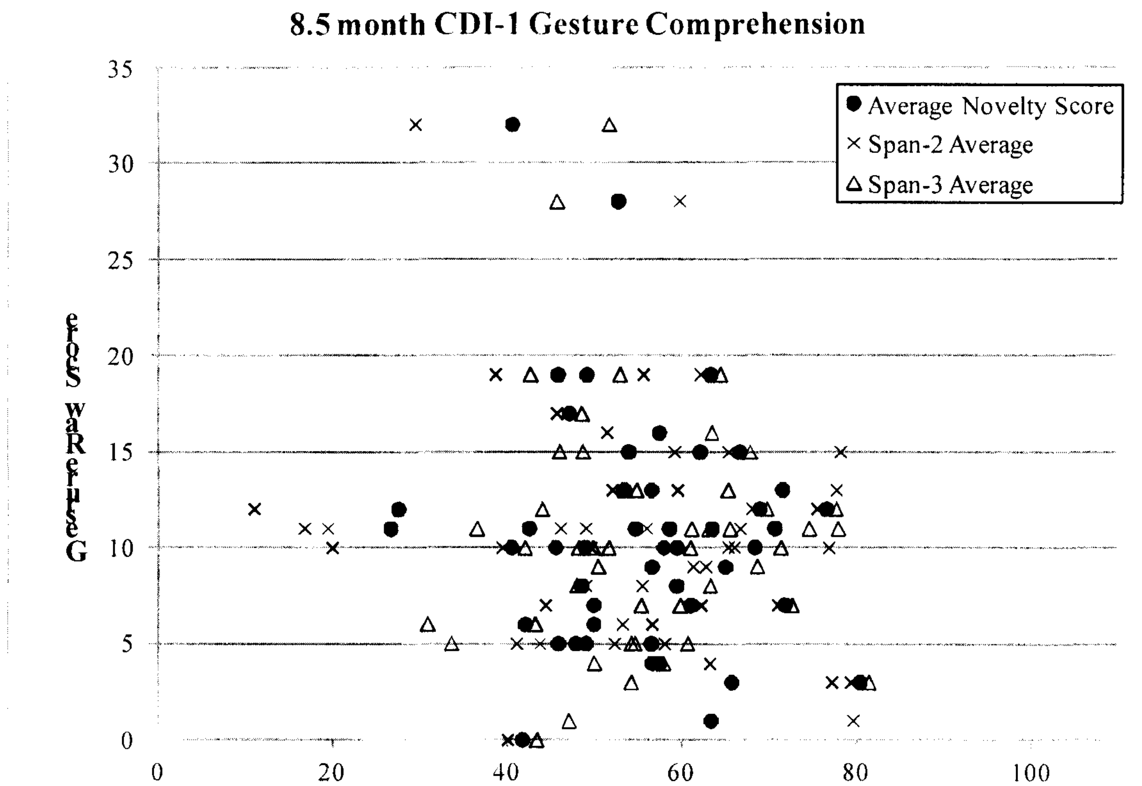

Figure 5-2. Scatterplots for CDI-1 Gesture Comprehension scores at 8.5 months and the VRM novelty scores.

Table 5-4

Correlation Matrix for the CDI-1 Measures at 8.5 Months

Measure	1	2	3	4	5
1. Overall Average Novelty Score	---				
p value (one-tailed)	---				
2. Average Novelty Score Span-2	.78	---			
p value (one-tailed)	*<.001*	---			
3. Average Novelty Score Span-3	.81	.27	---		
p value (one-tailed)	*<.001*	*.035*	---		
4. Vocab Comprehension (8.5 months)	-.12	-.24	.04	---	
p value (one-tailed)	*.215*	*.058*	*.404*	---	
5. Gesture Comprehension (8.5 months)	-.12	-.18	-.02	.69	---
p value (one-tailed)	*.21*	*.117*	*.448*	*<.001*	---

Note: Shaded boxes denote statistical significance of $p < .01$.

Does VRM Task Performance Correlate with Infants' Productive Language Ability 9 Months after Participating in the Study?

Correlation analyses were next conducted between the novelty score and the CDI-2 scores from a follow-up CDI-2 that was mailed to parents approximately 9 months after their lab visit. These analyses were conducted for only the subset of the sample (32 infants, age range 17.0–19.3 months old, $M = 17.6$, $SD = .57$) whose parents returned the follow-up CDI-2 that was mailed. First of all, as expected, Vocabulary Production at 17.5 months was significantly correlated with Vocabulary Production at 23.5 and 28.5 months. Using corrected CDI-2 scores, the overall average novelty score was significantly negatively correlated with Vocabulary Production (see Figure 5-5 and Table 5-6). Specifically, infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) had a smaller productive vocabulary 9 months later. Span-2 average and span-3 average novelty scores were also significantly negatively correlated with Vocabulary Production (Figure 5-5). These results suggest that infants who were *better* at remembering the familiarized images were *worse* off in their language ability at the later time points—contradicting the results of previous studies. However, as shown in Figure 5-5, there is a lot of variability in the relationship between VRM task performance and the Vocabulary Production measure. Therefore the weak negative correlation (although significant) is difficult to interpret. This puzzling pattern of results is returned to in the Discussion section.

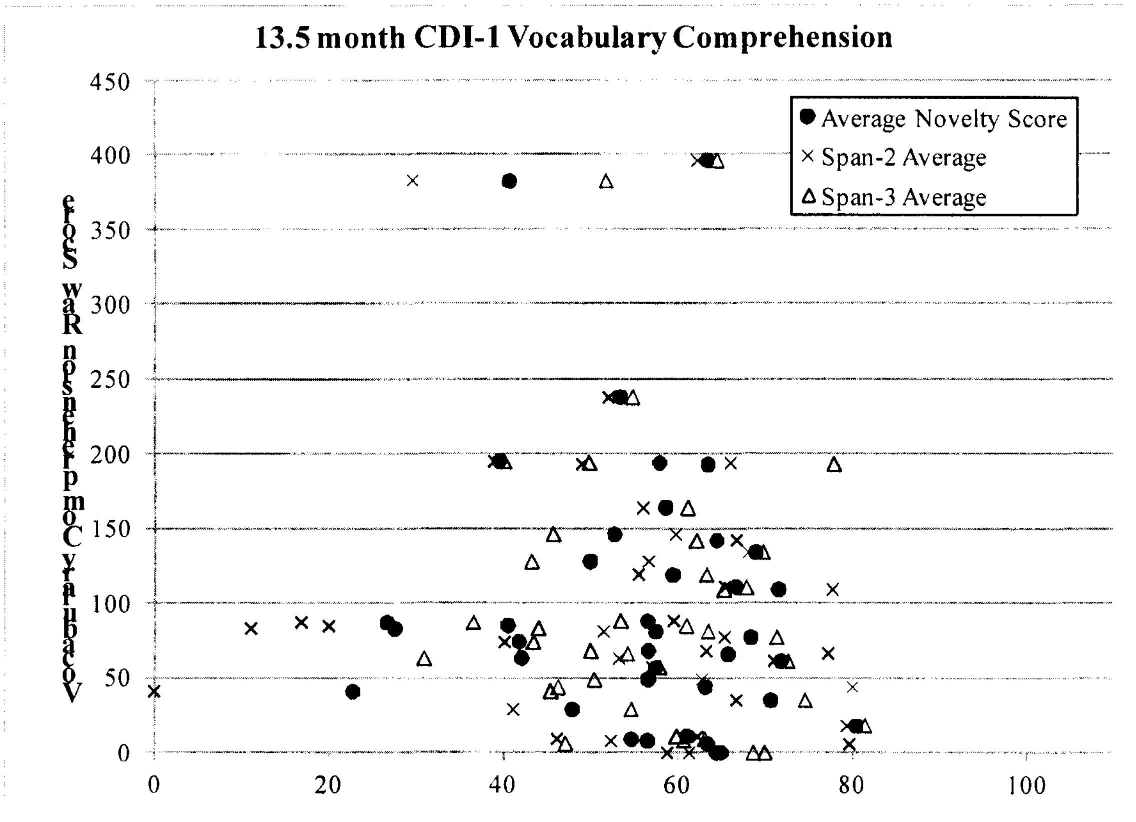

Figure 5-3. Scatterplots for CDI-1 Vocabulary Comprehension scores at 13.5 months and the VRM novelty scores.

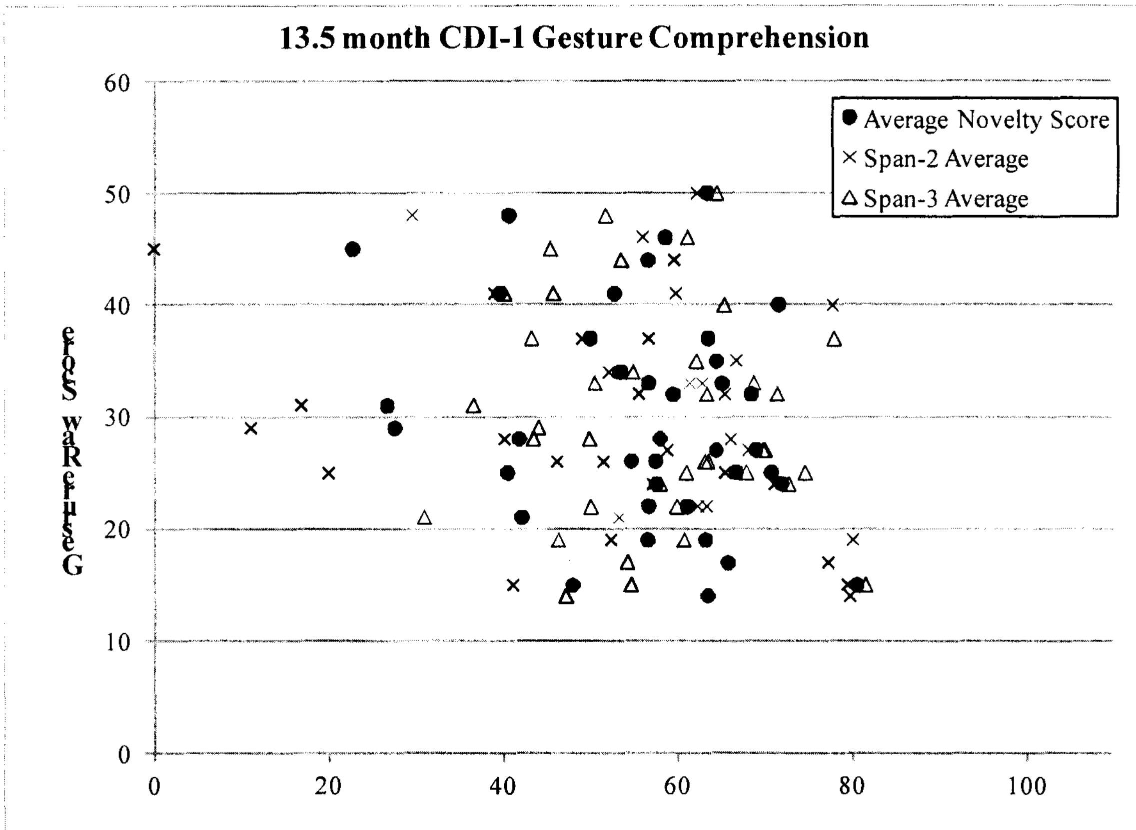

Figure 5-4. Scatterplots for CDI-1 Gesture Comprehension scores at 13.5 months and the VRM novelty scores.

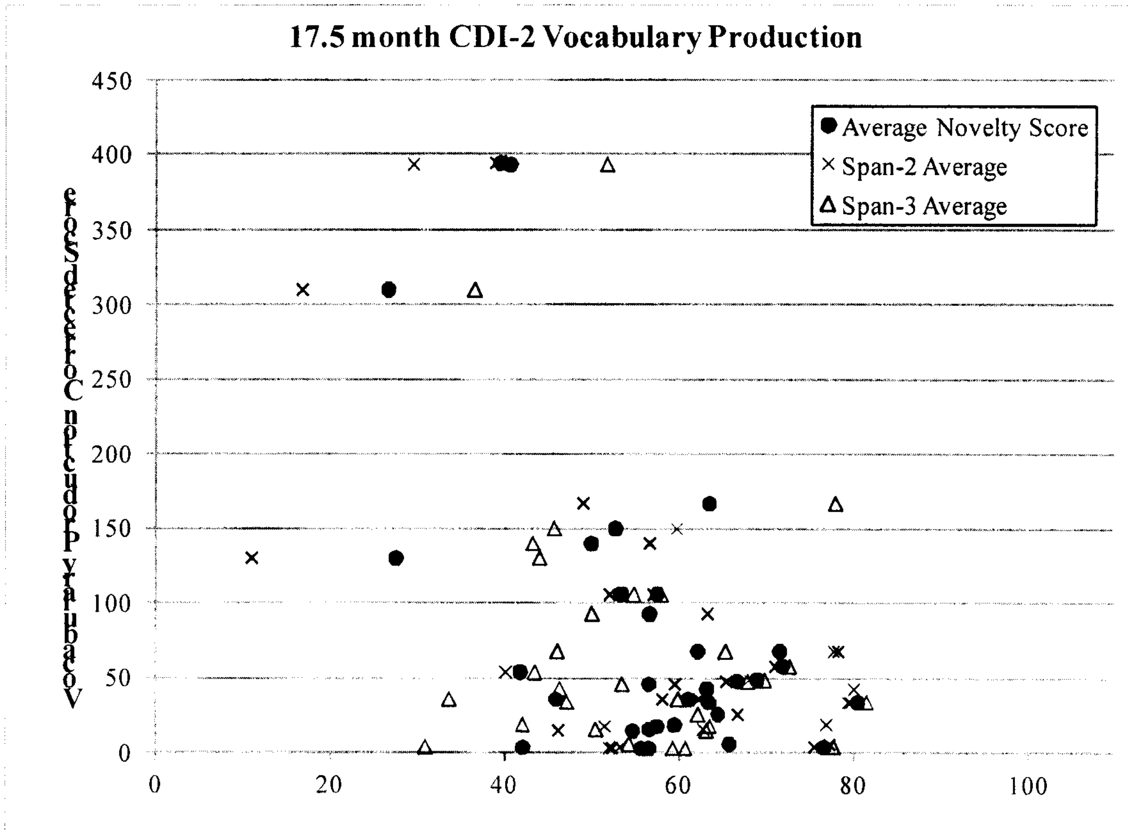

Figure 5-5. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 17.5 months and the VRM novelty scores.

Table 5-5

Correlation Matrix for the CDI-1 Measures at 13.5 Months.

Measure	1	2	3	4	5	6
1. Overall Average Novelty Score	---					
p value (one-tailed)	---					
2. Average Novelty Score Span-2	.85	---				
p value (one-tailed)	*<.001*	---				
3. Average Novelty Score Span-3	.83	.40	---			
p value (one-tailed)	*<.001*	*.007*	---			
4. Vocab Comprehension (13.5 months)	-.13	-.14	-.08	---		
p value (one-tailed)	*.22*	*.204*	*.325*	---		
5. Gesture Comprehension (13.5 months)	-.27	-.35	-.11	.67	---	
p value (one-tailed)	*.05*	*.018*	*.268*	*<.001*	---	
6. Vocab Production (13.5 months)[1]	-.19	-.22	-.14	.62	.52	---
p value (one-tailed)	*.122*	*.093*	*.198*	*<.001*	*<.001*	---

Note: Shaded boxes denote statistical significance of $p < .01$. Lightly shaded boxes denote statistical significance of $p < .10$ (marginal).

Table 5-6

Correlation Matrix for CDI-2 Vocabulary Production at 17.5, 23.5, and 28.5 Months

Measure	1	2	3	4	5	6
1. Overall Average Novelty Score	---					
p value (one-tailed)	---					
2. Average Novelty Score Span-2	.76	---				
p value (one-tailed)	*<.001*	---				
3. Average Novelty Score Span-3	.81	.24	---			
p value (one-tailed)	*<.001*	*.100*	---			
4. Vocab Production (17.5 months)	-.52	-.61	-.25	---		
p value (one-tailed)	*.001*	*<.001*	*.087*	---		
5. Vocab Production (23.5 months)	-.55	-.45	-.41	.87	---	
p value (one-tailed)	*<.001*	*.004*	*.008*	*<.001*	---	
6. Vocab Production (28.5 months)	-.49	-.34	-.50	.63	.76	---
p value (one-tailed)	*.004*	*.041*	*.003*	*<.001*	*<.001*	---

Note: Shaded boxes denote statistical significance of $p < .01$. Lightly shaded boxes denote statistical significance of $p < .10$ (marginal).

Does VRM Task Performance Correlate with Infants' Productive Language Ability 15 Months after Participating in the Study?

Correlation analyses were conducted between the novelty score and the CDI-2 scores from the follow-up CDI-2 that was mailed to parents approximately 15 months after their lab visit in order to address this question. Not all of the parents returned the follow-up CDI-2 that was mailed, so these analyses were conducted for only a subset of the sample (35 infants, age range 22.8–24.9 months old, $M = 23.4$, $SD = .57$). Using corrected CDI-2 scores, the overall average novelty score was significantly negatively correlated with Vocabulary Production (see Table 5-6 and Figure 5-6). Specifically, infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) had smaller productive vocabularies 15 months later. Span-2 average and span-3 average novelty scores were also significantly negatively correlated with Vocabulary Production (see Figure 5-6). This is the same pattern that was found with the vocabulary production measure at 17.5 months old.

The relationship between novelty scores on the VRM task and performance on the CDI-2 grammar measures at approximately 23.5 months old was investigated next. The overall average novelty score was significantly negatively correlated with the use of inflection (see Figure 5-7), but was not significantly correlated with the other grammatical measures (see Table 5-7 and Figure 5-8). The span-2 average and span-3 average novelty scores were also negatively correlated with the use of inflection (see Figure 5-7), but were not significantly correlated with the other grammatical measures (Figure 5-8). This pattern of results suggests that infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) at 8.5 months of age were less likely to use regular inflection when they were 23.5 months of age. This suggests that the infants who performed more poorly on the VRM task had more advanced grammatical abilities. However, as shown in the scatterplots (Figures 5-6 and 5-7), there is a lot of variability in the relationship between VRM task performance and the CDI-2 measures. Therefore these weak negative correlations (although significant) are difficult to interpret. These puzzling findings are revisited in the Discussion section.

Does VRM Task Performance Correlate with Infants' Productive Language Ability 20 Months after Participating in the Study?

Finally, correlation analyses were conducted between novelty scores and the CDI-2 scores from the follow-up CDI-2 that was mailed to parents approximately 20 months after their lab visit. These analyses were conducted for only the subset of the sample (29 infants, aged 27.8–31.0 months old, $M = 28.5$, $SD = .73$) whose parents returned this follow-up CDI-2. Using corrected CDI-2 scores, the overall average novelty score was significantly negatively correlated with Vocabulary Production at age 28.5 months (see Table 5-6 and Figure 5-9). Specifically, infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) at 8.5 months had smaller productive vocabularies 20 months later. Span-3 average novelty score was also significantly negatively correlated with Vocabulary Production (Figure 5-9). This is the same pattern that was found with the vocabulary production measure at 17.5 and 23.5 months old, but as with those correlations, the scatterplot for these correlations (Figure 5-9) illustrates the high level of variability in the relationship between VRM task performance and the CDI-2 measures. This makes the weak (significant) negative correlations difficult to interpret.

Table 5-7

Correlation Matrix for CDI-2 Grammatical Measures at 23.5 Months

Measure	1	2	3	4	5	6
1. Overall Average Novelty Score	---					
p value (one-tailed)	---					
2. Average Novelty Score Span-2	.82	---				
p value (one-tailed)	*<.001*	---				
3. Average Novelty Score Span-3,	.83	.37	---			
p value (one-tailed)	*<.001*	*.015*	---			
4. Inflection (23.5 months)	-.58	-.49	-.43	---		
p value (one-tailed)	*<.001*	*.002*	*.005*	---		
5. Irregulars (23.5 months)	-.24	-.29	-.07	.66	---	
p value (one-tailed)	*.086*	*.047*	*.342*	*<.001*	---	
6. Over-Regulars (23.5 months)	.13	.10	.18	.26	.53	---
p value (one-tailed)	*.228*	*.297*	*.152*	*.066*	*.001*	---

Note: Shaded boxes denote statistical significance of p <.01.

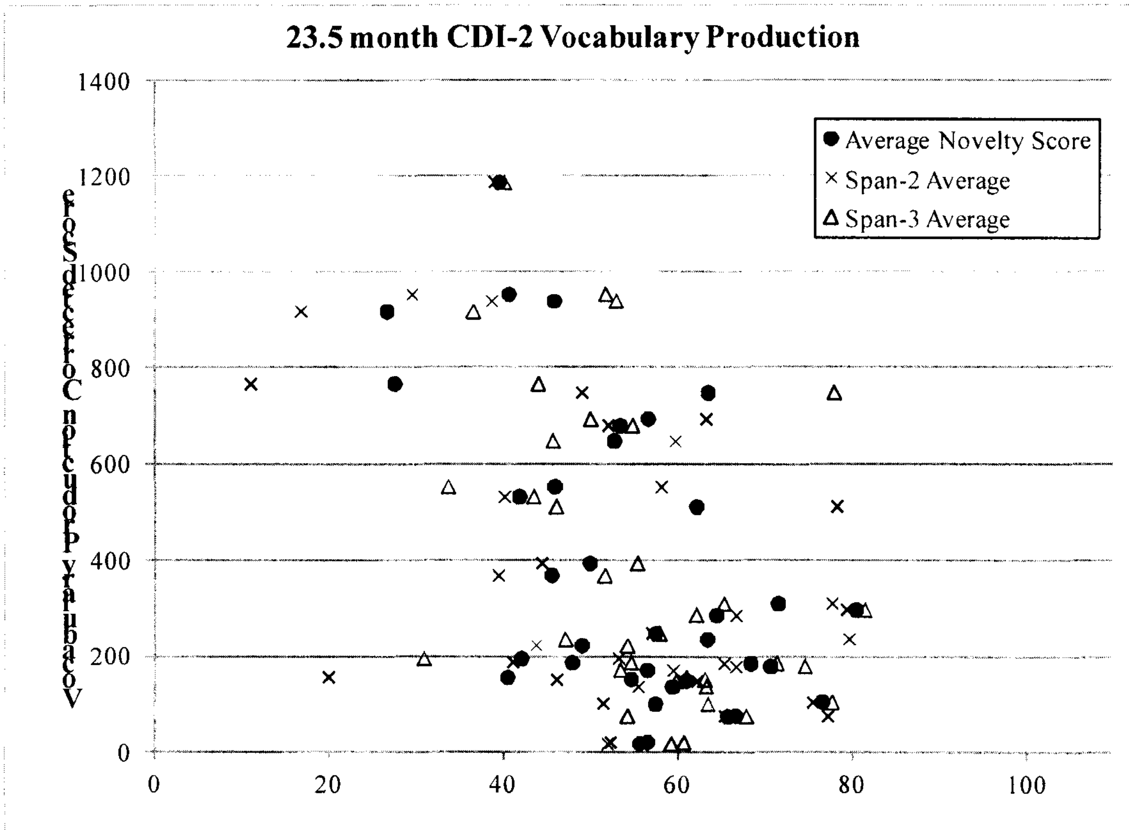

Figure 5-6. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 23.5 months and the VRM novelty scores.

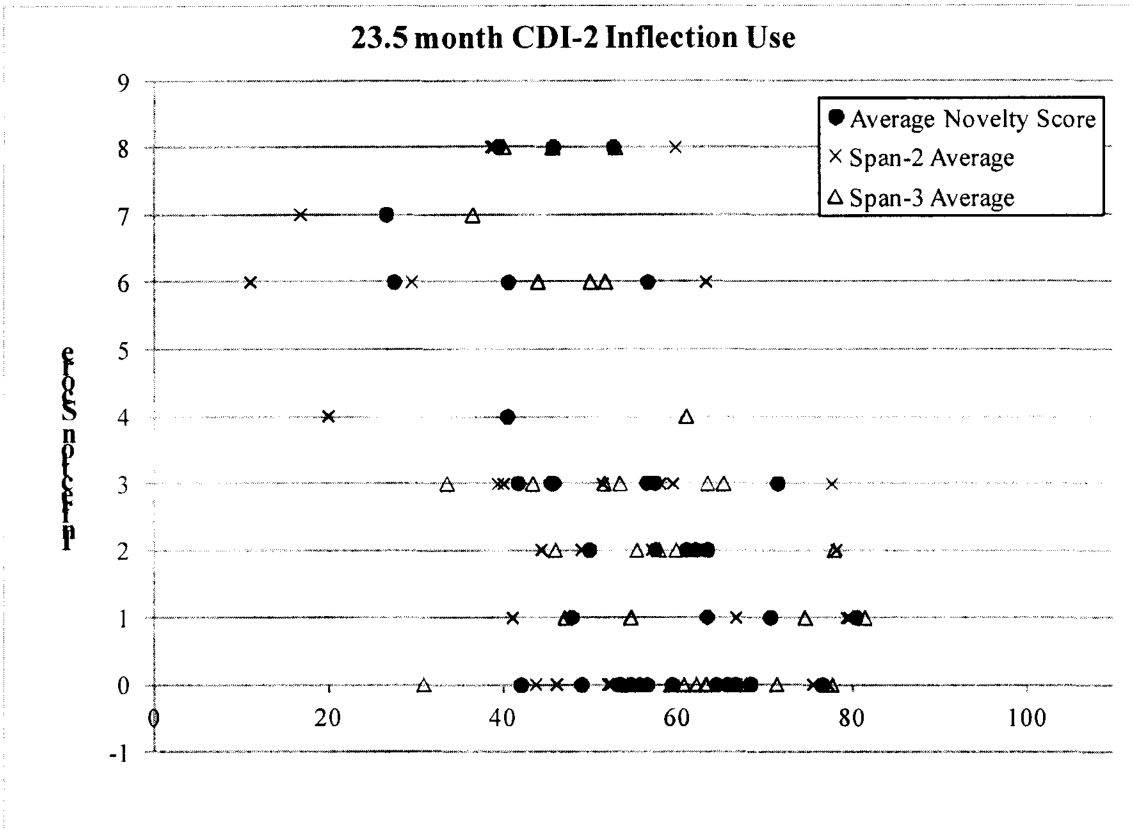

Figure 5-7. Scatterplots for CDI-2 Inflection scores at 23.5 months and the VRM novelty scores.

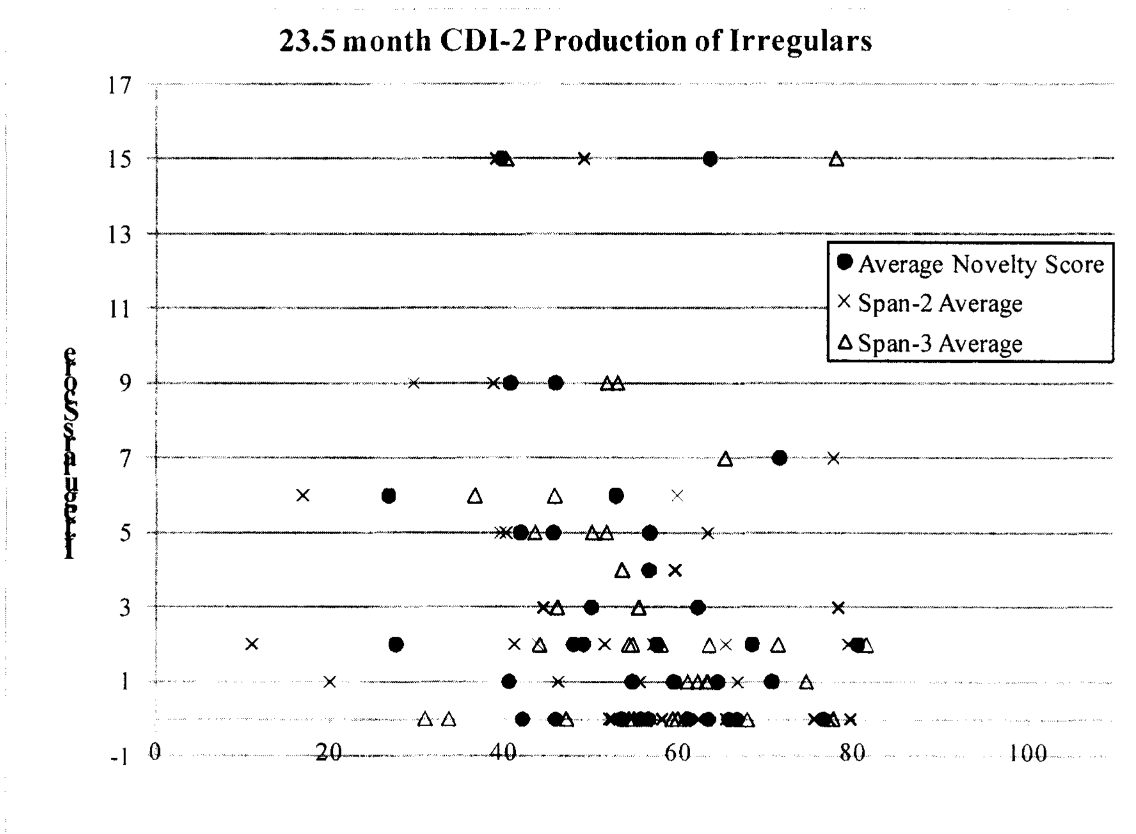

Figure 5-8. Scatterplots for CDI-2 Irregulars scores at 23.5 months and the VRM novelty scores.

Next the relationship between novelty scores on the VRM task and performance on the CDI-2 grammar measures at approximately 28.5 months old was investigated. The overall average novelty score was marginally negatively correlated with the use of irregular nouns and verbs (see Figure 5-10), but was not significantly correlated with the other grammatical measures (see Table 5-8 and Figure 5-11). The span-2 average novelty score was not significantly correlated with any of the grammatical measures, but the span-3 average novelty score was significantly negatively correlated with the use of irregular nouns and verbs (see Figures 5-10 and 5-11). This pattern of results suggests that infants who preferred to look at the novel stimulus (remembered the familiarized stimulus) at 8.5 months of age were less likely to use irregular nouns and verbs when they were 28.5 months of age. This suggests that the infants who performed more poorly on the VRM task had more advanced grammatical abilities. Like many of the other significant correlations, this is a puzzling finding, and contradictory to previous studies. However, like the other significant negative correlations, the scatterplots (Figures 5-10 and 5-11) show that there is a lot of variability in the relationship between VRM task performance and the CDI-2 measures. Thus the weak negative correlations (although significant) are difficult to interpret. Some possible explanations for these patterns are discussed in the Discussion section.

Summary of VRM Results

Overall, performance on the VRM task at 8.5 months old was not significantly correlated with receptive language abilities either at the same time point, or 5 months later (when the infants were an average of 13.5 months old). Interestingly, performance on the VRM task was *negatively* correlated with productive language ability at 17.5, 23.5, and 28.5 months old, such that infants who demonstrated better recognition memory ability had smaller productive vocabularies at the later time points. The significant grammar correlations were also negative, such that infants who preferred to look at the novel stimulus at 8.5 months of age were *less* likely to use regular inflection when they were 23.5 months of age, and *less* likely to produce irregular nouns and verbs when they were 28.5 months of age.

Table 5-8

Correlation Matrix for CDI-2 Grammatical Measures at 28.5 Months

Measure	1	2	3	4	5	6
1. Overall Average Novelty Score	---					
p value (one-tailed)	---					
2. Average Novelty Score Span-2	.79	---				
p value (one-tailed)	*<.001*	---				
3. Average Novelty Score Span-3	.81	.27	---			
p value (one-tailed)	*<.001*	*.079*	---			
4. Inflection (28.5 months)	-.20	-.28	.12	---		
p value (one-tailed)	*.151*	*.075*	*.274*	---		
5. Irregulars (28.5 months)	-.39	-.27	-.42	.68	---	
p value (one-tailed)	*.018*	*.086*	*.013*	*<.001*	---	
6. Over-Regulars (28.5 months)	-.15	-.11	-.18	.54	.61	---
p value (one-tailed)	*.212*	*.295*	*.186*	*.001*	*<.001*	---

Note: Shaded boxes denote statistical significance of p <.01.

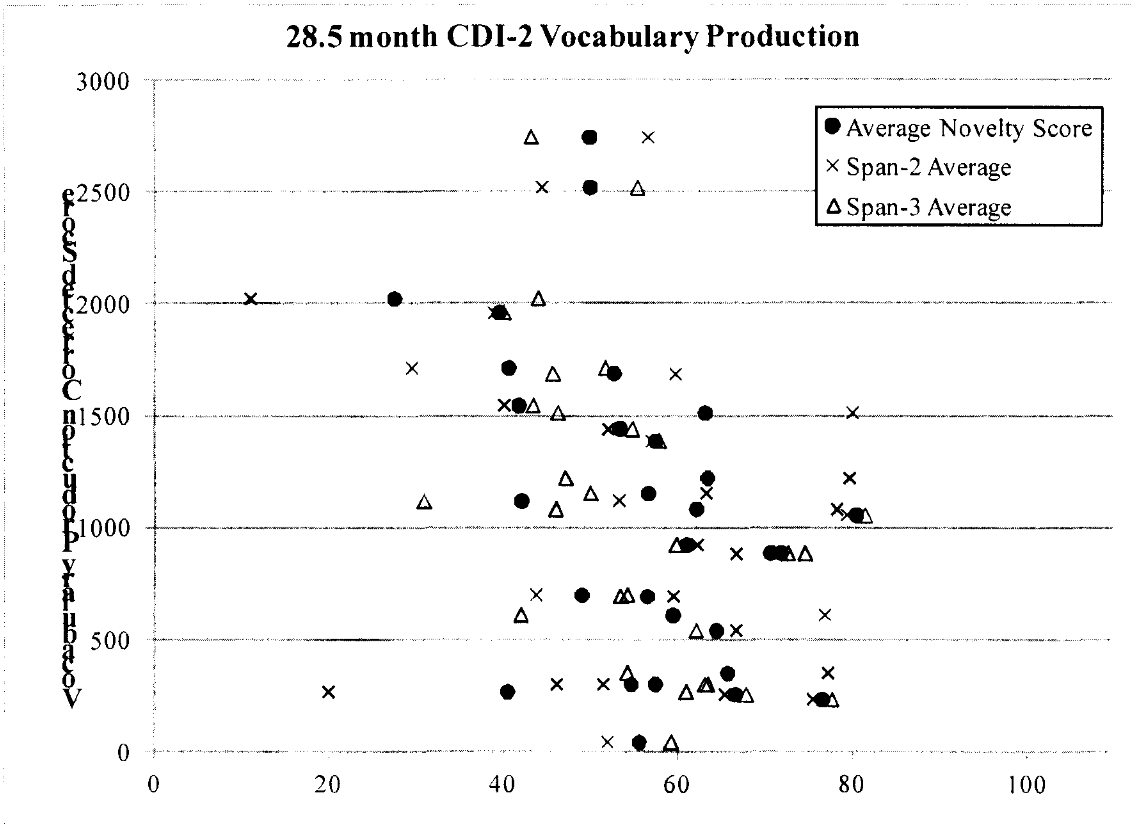

Figure 5-9. Scatterplots for CDI-2 Corrected Vocabulary Production scores at 28.5 months and the VRM novelty scores.

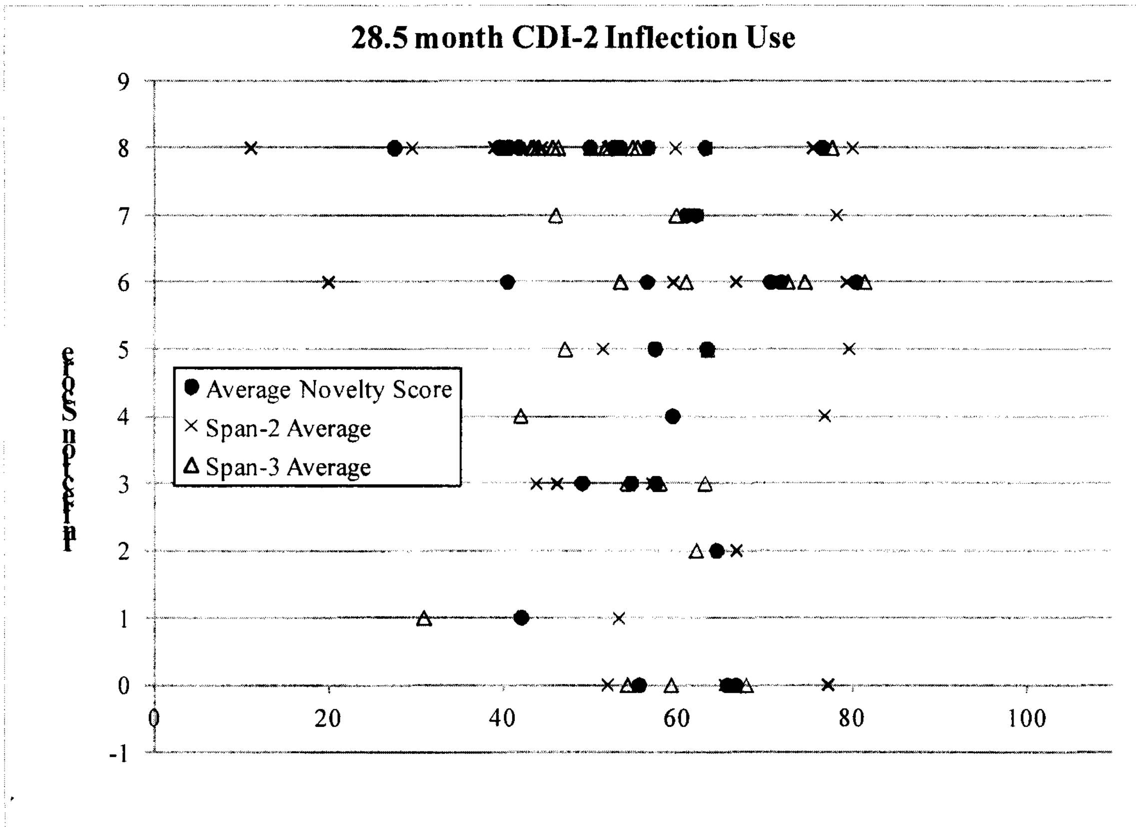

Figure 5-10. Scatterplots for CDI-2 Inflection scores at 28.5 months and the VRM novelty scores.

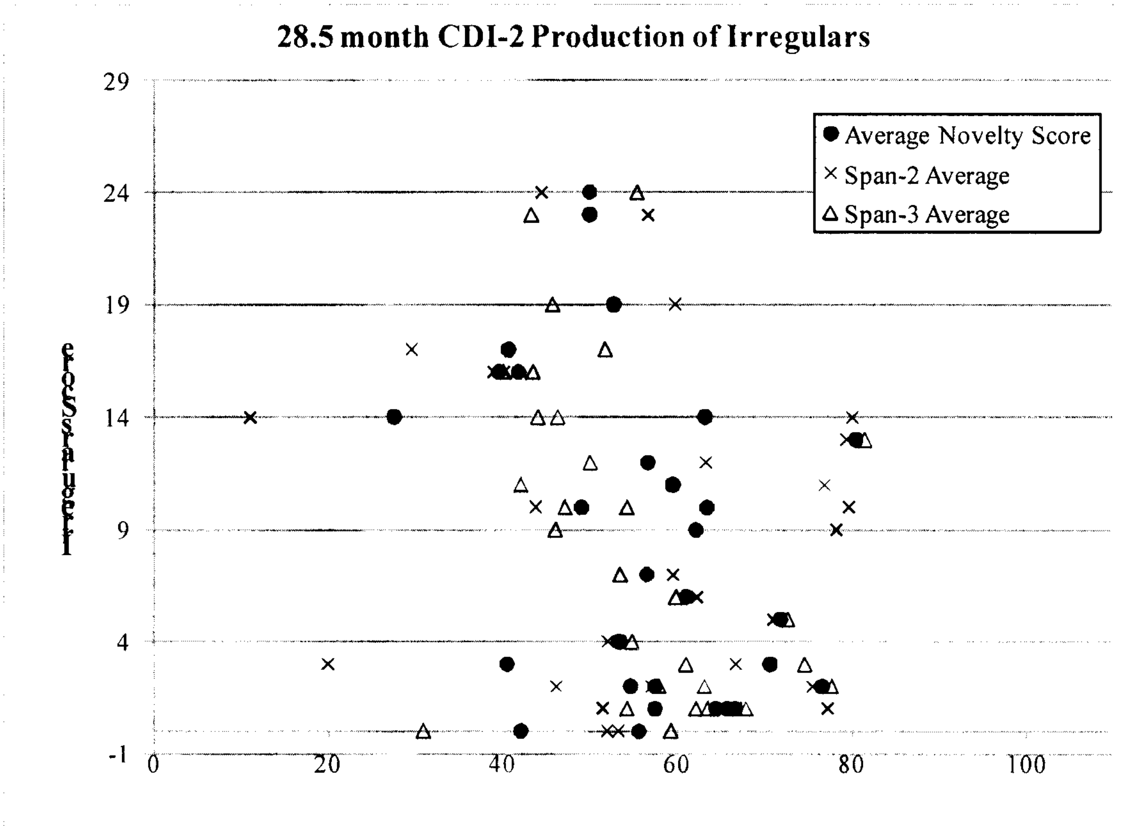

Figure 5-11. Scatterplots for CDI-2 Irregulars scores at 28.5 months and the VRM novelty scores.

Discussion

Contrary to findings by Rose and colleagues, infants in the current study did not demonstrate a group pattern of recognition memory. In addition, although previous studies have found a *positive* relationship between recognition memory and vocabulary ability, in the current study there was a *negative* relationship. The remainder of this section discusses how and why the results of the current study diverge from those in previous studies, and offers some possible explanations for the negative correlations found in the current study.

The infants in the current study, unlike those in previous studies by Rose and colleagues, did not exhibit an overall novelty preference. Specifically, they did not demonstrate recognition memory, despite the fact that the current paradigm was based on that used in Rose et al. (2001). Importantly, there was a major methodological difference between the current study and that in Rose et al. (2001). In particular, Rose and colleagues used real three-dimensional objects in their recognition memory task, whereas static images of three-dimensional objects were used in the current study. It is likely that the infants in the current study did not find the static images as interesting as actual objects, and thus got bored or fatigued early in the experiment. One way to adjust the current method to control for this problem would be to reduce the trial length. In the VRM task, the familiarization trials were each 10 seconds long and the test trials were also 10 seconds long. These trial lengths were chosen based on the trial length that Rose et al. (2001) determined to be appropriate for infants this age, but shorter trials were likely warranted in the current experiment due to the difference in the saliency of 2-dimensional versus 3-dimensional stimuli. It could be that if the infants had shorter familiarization and shorter test trials (e.g., for 5 seconds), that they would have maintained their attention throughout the experiment and demonstrated recognition memory (i.e., a novelty preference). Unfortunately it is not possible to just code, for example, the first 5 seconds of each trial because infants' looking behavior during later trials was likely affected by the length of the preceding trials. For example, if infants were getting bored during the early trials, that could have led them to look at the stimuli for less time later in the experiment.

A second divergence from previous research was in the pattern of correlations in the current study. In previous studies, recognition memory performance during infancy has been found to *positively* correlate with vocabulary ability at 4, 7, and 11 years old (Fagan, 1984a; Fagan & McGrath, 1981; Rose & Feldman, 1995). However, in the current study, recognition memory performance as assessed by the VRM task was *negatively* correlated with productive vocabulary ability at 17.5, 23.5, and 28.5 months old. Because there was not an overall pattern of learning (i.e., recognition memory) during the VRM task, this pattern of correlations is difficult to interpret.

I am not aware of any studies specifically investigating the correlation between recognition memory performance in infancy and grammatical ability at later ages. However, a few previous studies found a positive correlation between recognition memory performance and receptive and expressive language at 2.5, 3, 4, and 6 years old (Rose, Feldman, & Wallace, 1992; Rose et al., 1991; L. Thompson et al., 1991). Based on those findings, a positive correlation between VRM task performance and the CDI-2 grammatical measures was expected. However, as with the productive vocabulary measure, there was a negative correlation between VRM task performance at 8.5 months old and CDI-2 grammatical ability at later ages. Specifically, novelty scores on the VRM were negatively correlated with the use of regular inflection (e.g., adding 'ed' to mark past tense) at 23.5 months old, and with the production of irregular nouns and verbs (e.g., went) at 28.5 months old.

The negative correlation with irregular nouns and verbs is actually consistent with the negative correlation with productive vocabulary because irregular nouns and verbs are actually lexical items, rather than grammatical in nature. Unlike the use of regular inflection, which requires the learning of a rule that can be applied to many words in a class, irregular nouns and verbs (by definition) have to just be memorized. The use of regular inflection, on the other hand, represents an early grammatical skill. Nonetheless, the pattern of *negative* correlations is puzzling because it suggests that the children who are poorer learners on the VRM task are the children who have more advanced grammatical skills later on. However, there is good reason to believe that the infants were not maintaining attention throughout the VRM task. In particular, the average looking time per trial was 5.8 seconds (just a little more than half of the 10 second trial length), and some infants never looked for more than 4 or 5 seconds during a trial. Because overall infants did not appear to maintain attention during this task, the correlations between looking time during the task and language outcomes are likely not very meaningful.

Conclusion

Results of the current study did not successfully replicate previous results that 8.5-month-olds can remember familiarized visual images. It is therefore possible that the VRM task is not appropriate for deaf infants who are chronologically older than these normal-hearing 8.5-month-olds. In the presentation of results from deaf infants on the VRM task (Chapters III and VI) conclusions are tempered accordingly.

CHAPTER VI

THE SPOKEN LANGUAGE DEVELOPMENT OF DEAF INFANTS AND ITS RELATION TO VISUAL SEQUENCE LEARNING AND VISUAL RECOGNITION MEMORY

This chapter presents data on the potential link between nonverbal cognitive abilities (visual sequence learning and visual recognition memory) and spoken language outcomes for deaf infants who use cochlear implants.

The goal of the current study was to determine the relation between deaf infants' nonverbal cognitive abilities during infancy (VSL and VRM task performance) and spoken language ability after a period of cochlear implant use. However, because the sample of deaf infants is relatively small, largely descriptive results are presented. This includes group and individual vocabulary scores, as well as descriptive analyses for different subgroups of the deaf children.

Method

Participants

The participants were 18 deaf infants (11 female) recruited through the Heuser Hearing Institute in Louisville, KY and the Infant Speech Lab at the Indiana University School of Medicine in Indianapolis, IN (see Table 3-1 for individual demographic information). One additional infant was tested in the VSL task, but was excluded from the current analyses for failing to return any CDIs. All infants had congenital severe to profound hearing loss and were either scheduled to receive a cochlear implant or had a cochlear implant activated within 24 hours of participation in the VSL and/or VRM tasks. At the time they participated in the VSL and/or VRM tasks, 17 of the infants used bilateral hearing aids and one infant had already received a cochlear implant, which had been activated the day before study participation.

Experimental Measures

VSL task. All 18 infants were tested on the VSL task. The VSL task relies on reaction time to assess how well infants learned a simple repeating 3-item spatiotemporal sequence. See Chapter II for details about the task Apparatus, Stimuli, and Procedure, as well as data collection, eye movement coding, and the calculation of the dependent variables. Details of the deaf children's performance on the VSL task are described in Chapter III.

VRM task. Thirteen of the deaf infants completed the Visual Recognition Memory (VRM) task. Five additional infants were tested on the VRM, but the data for 2 infants were unusable due to experimenter error and the other 3 infants did not complete the task. See Chapter II for details about the task Apparatus, Stimuli, and Procedure, as well as data collection, eye movement coding, reliability coding, and the calculation of the dependent variables. Details of the deaf children's performance on the VRM task are described in Chapter III.

Language Measures

In order to measure the relations between VSL/VRM task performance in infancy and English spoken language abilities at later time points, parents were asked to fill out language questionnaires about their child. The MacArthur-Bates Communicative Development Inventories (Fenson et al., 2006) were used—both the 'Words and Gestures' (CDI-1) and the 'Words and Sentences' (CDI-2) form. Detailed descriptions of the two forms can be found in Chapter II. As a reminder, parents were instructed to specify whether their child understood/spoke the word manually (M), verbally (V), or both (B), and only words marked as V or B were included when tallying the CDI scores. At the time of last CDI, no child was producing more than 250 words. Therefore, we were unable to examine early grammatical development in this small sample.

Results

CDIs were sent out at 12 unique post-cochlear implantation intervals. Almost every form was returned at the first two time points, but no more than 9 CDIs were returned at any of the later time points (see Table 6-1). The raw scores for all of the CDIs that were returned are presented in Figures 6-1 through 6-3. In the following sections the CDI data are presented by condensing across cochlear implantation age groups, followed by some descriptive information about how infants' performance on the VSL and VRM tasks relates to their later CDI scores.

Implantation Age Groups

We split the sample into three groups based on their age at cochlear implantation. In Figures 6-1 through 6-3 the three implantation age groups are indicated by different line types. The first group consisted of the three infants who received their cochlear implants prior to 12 months of age (represented by dotted lines), the second group consisted of the nine infants who received their cochlear implants between 12 and 17 months of age (represented by solid lines), and the third group consisted of the six infants

Table 6-1

Counts for CDIs Returned at each of the Post-Cochlear Implantation Time Points

ID	Up to 2 weeks post-implantation	Months Post-Cochlear Implantation												# of CDIs
		1	**2**	**3**	**4**	**5**	**6**	**7 - 8**	**9**	**10 -11**	**12**	**15**	**18**	
A	y	y	n	y	n	n	y	n	y	n	y	y	y	*8*
B	y	y	n	y	n	y	n	n	n	n	y	n	n	*5*
C	n	n	n	n	n	n	y	n	n	n	y	n	n	*2*
D	y	y	y	n	n	n	y	n	n	n	y	y	n	*6*
E	n	n	n	y	y	y	n	n	y	n	n	n	n	*4*
F	y	n	n	y	y	n	n	n	n	n	n	n	n	*3*
G	n	n	n	n	n	n	y	n	n	n	n	n	n	*1*
H	n	y	y	y	y	n	y	n	y	n	y	y	n	*8*
I	y	y	n	n	y	n	n	n	y	n	y	y	n	*6*
J	y	y	n	y	y	y	n	n	y	n	y	y	y	*9*
K	y	y	y	y	y	y	y	n	n	n	n	n	*n/a*	*7*
L	y	y	n	y	n	y	n	n	n	n	n		*n/a*	*4*
M	y	y	n	n	n	n	n	n	n	n	n	n	n	*2*
N	y	y	y	y	n	y	y	y	y	y	y	y	y	*12*
O	y	y	y	n	n	n	n	y	y	y	y	y	y	*9*
P	y	y	y	n	y	n	y	y	n	n	n	n	n	*6*
Q	y	y	y	n	y	n	y	y			*n/a*			*6*
R	y	y	n	n	y	y				*n/a*				*4*
TOTAL data points	*14*	*14*	*7*	*9*	*9*	*7*	*9*	*4*	*7*	*2*	*9*	*7*	*4*	

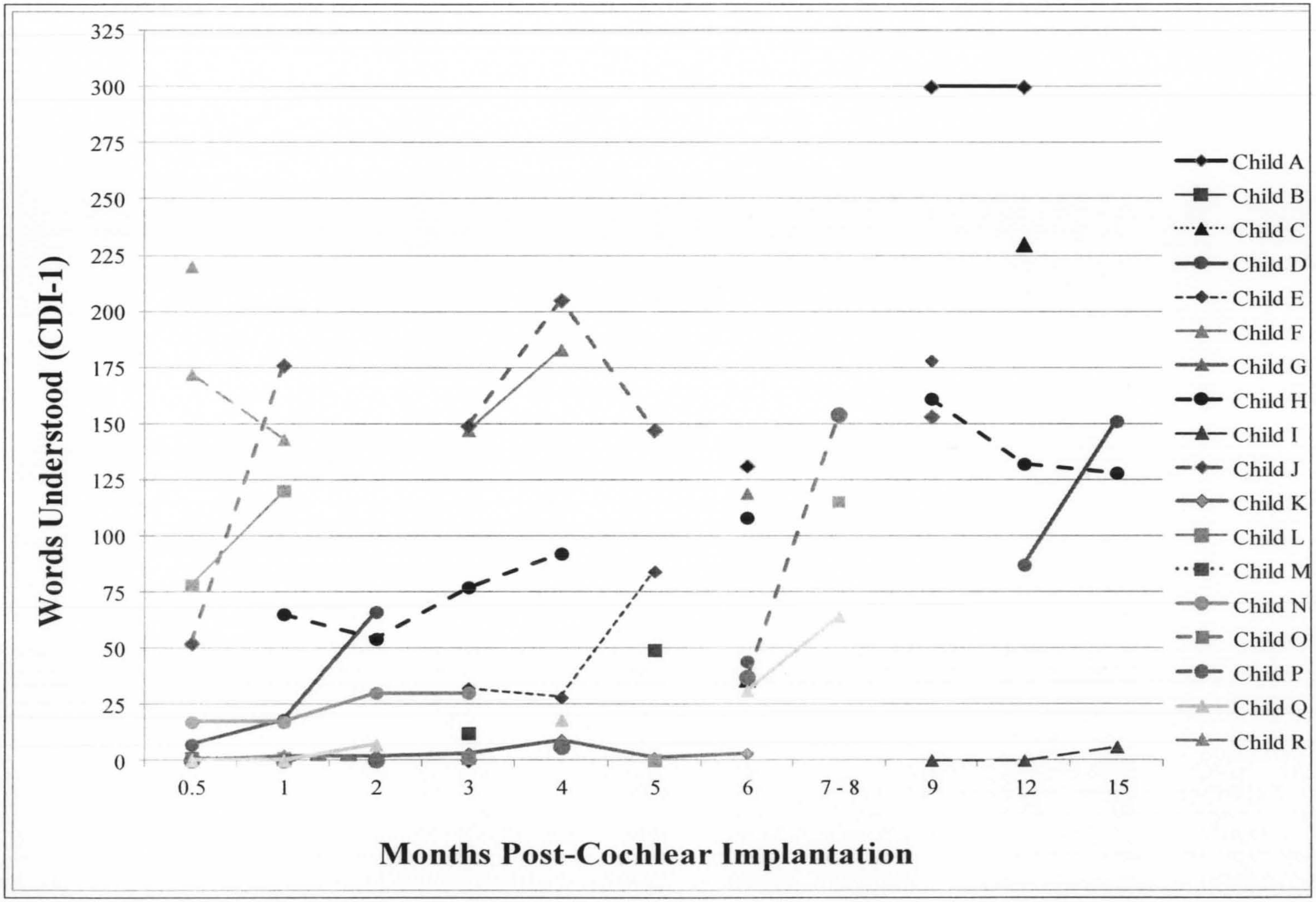

Figure 6-1. Deaf children's individual vocabulary comprehension scores from the CDI-1.

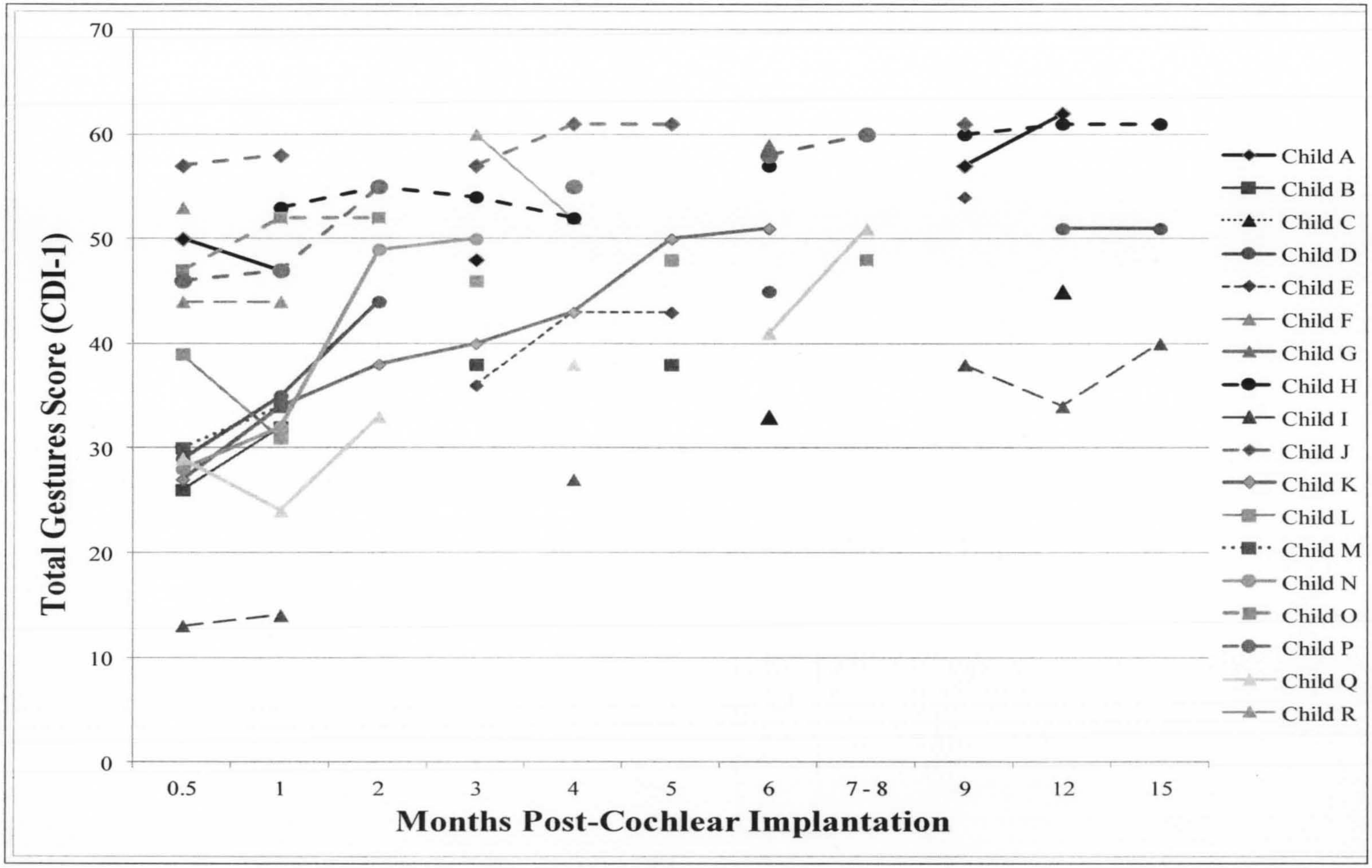

Figure 6-2. Deaf children's individual gestures scores from the CDI-1.

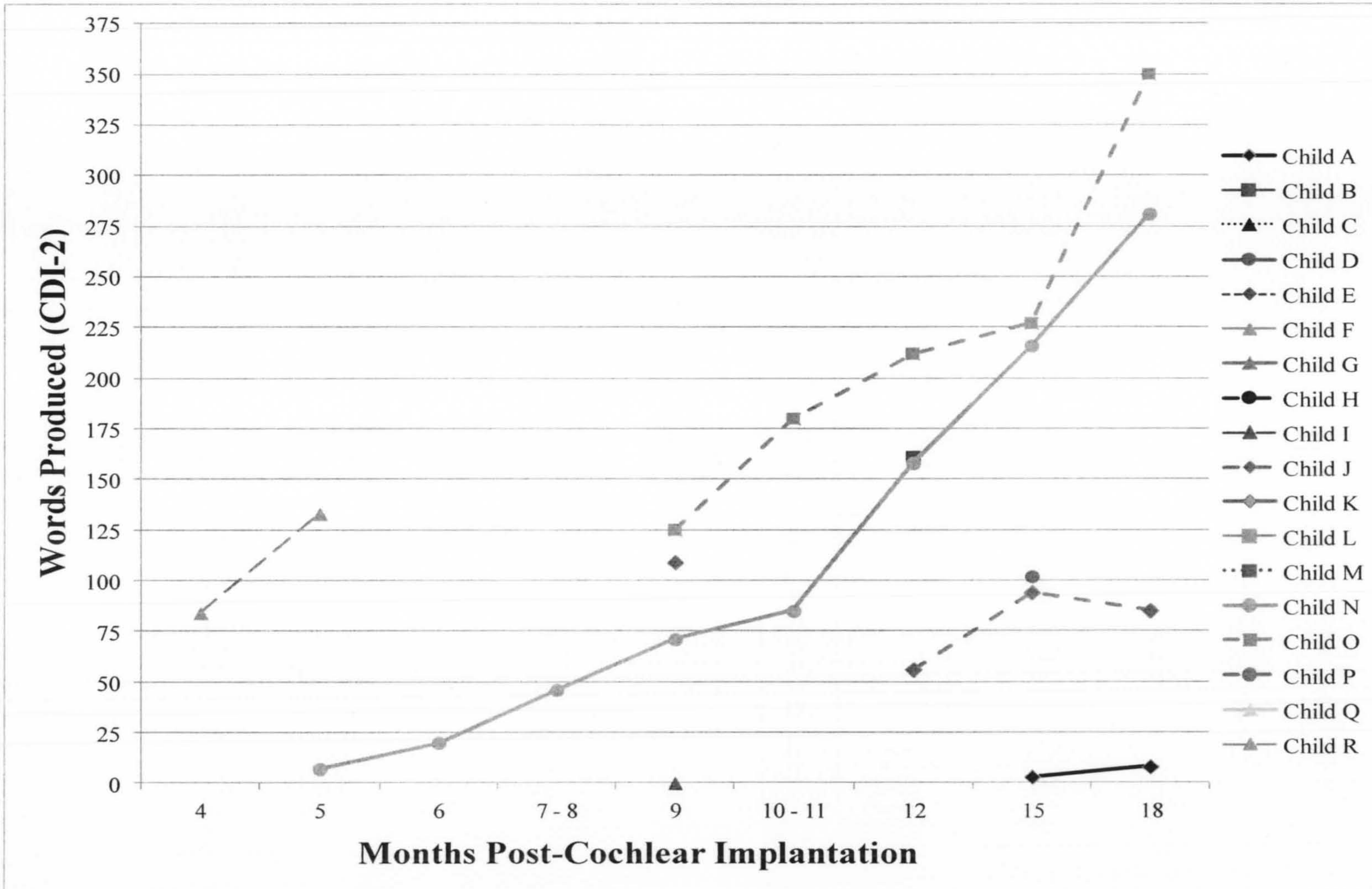

Figure 6-3. Deaf children's individual vocabulary production scores from the CDI-2.

Table 6-2

Results from the Growth Curve Analyses between the VSL Task and CDI-1 Vocabulary Comprehension Score

	RT Difference Score			**Correct Anticipatory Looks (Phase 1)**			**Correct Anticipatory Looks (Phase 2)**		
Parameter	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**
Fixed Effect									
Intercept (β_{00})	31.72	17.79	.092	32.03	17.53	.085	32.17	17.74	.087
Months slope (β_{10})	7.94	2.82	.012	8.78	3.80	.035	3.69	4.05	.376
VSL DV (β_{11})	7.39	7.52	.340	-0.37	0.96	.706	1.14	0.86	.204
Level-1 variance (σ^2)	1914.54			1932.53			1881.76		
Intercept variance (τ_{00})	4184.96			4026.10			4205.04		

Table 6-3

Results from the Growth Curve Analyses between the VSL Task and CDI-1 Total Gestures Score

	RT Difference Score			**Correct Anticipatory Looks (Phase 1)**			**Correct Anticipatory Looks (Phase 2)**		
Parameter	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**
Fixed Effect									
Intercept (β_{00})	38.28	2.91	< .001	37.88	2.86	< .001	37.91	2.97	< .001
Months slope (β_{10})	1.64	0.28	< .001	1.63	0.41	.009	1.78	0.57	.007
VSL DV (β_{11})	-1.35	0.86	.134	0.07	0.10	.490	0.02	0.13	.893
Level-1 variance (σ^2)	14.74			13.43			13.48		
Intercept variance (τ_{00})	138.24		< .001	142.07			143.66		

Table 6-4

Results from the Growth Curve Analyses between the VSL Task and CDI-2 Vocabulary Production Score

Parameter	**RT Difference Score** Parameter Estimate	SE	*p* value	**Correct Anticipatory Looks (Phase 1)** Parameter Estimate	SE	*p* value	**Correct Anticipatory Looks (Phase 2)** Parameter Estimate	SE	*p* value
Fixed Effect									
Intercept (β_{00})	4.86	39.03	.905	17.05	52.60	.757	-3.84	45.15	.935
Months slope (β_{10})	3.82	2.24	.149	5.00	6.21	.458	-4.84	5.56	.424
VSL DV (β_{11})	117.58	11.70	$< .001$	1.33	1.57	.436	4.23	1.19	.016
Level-1 variance (σ^2)	455.69			488.39			433.81		
Intercept variance (τ_{00})	7029.80			12125.32			8256.09		

who received their cochlear implants between 18 and 24 months (represented by dashed lines). The three implantation groups are too small to do statistical comparisons, but in Figure 6-2 the children in the latest implantation group appear to have higher gestures scores. The vocabulary comprehension scores (Figure 6-1) appear to be quite variable for all three implantation groups, and there are too few children with vocabulary production data to elicit any kind of pattern (Figure 6-3).

Testing the Relation between Experimental Task Performance and the CDI

As discussed in Chapter III, there was quite a lot of variability in how infants performed on the VSL task (see Figures 3-1 through 3-3 in that chapter) and on the VRM task (see Figures 3-5 and 3-6). Growth curve analysis (using HLM 7 software; Raudenbush, Bryk, & Congdon, 2011) was used to examine the relation between infants performance on the two experimental tasks and their reported CDI scores over the first 18 months of cochlear implant use. One advantage to using growth curve analysis is that it allows for unequally-spaced data and for irregular time points (i.e., different numbers of data points per participant). In addition, it can be used with relatively small sample sizes (typically a minimum sample of about 20 participants is recommended).

Separate analyses were run for each of the different measures from the CDI: the CDI-1 vocabulary comprehension score, the CDI-1 total gestures score, and the CDI-2 vocabulary production score. CDI scores were used as the outcome variable for each time point. For each analysis time using a cochlear implant (in months) was the level-1 predictor and the experimental dependent variable (which differed across the VSL and VRM tasks) was the level-2 predictor. Because there was a meaningful zero for both predictors, they were both entered into the growth curve model uncentered. We ran a linear growth curve analysis where the intercept and the slope (i.e., the change in CDI score from one month to the next) were all allowed to randomly vary. We allowed these predictors to randomly vary because we expected the growth in vocabulary score to differ within the group. For more details on growth curve modeling see Singer and Willett (2003).

The VSL Task. On the VSL task there were three dependent variables: the RT difference score, correct anticipatory looks during Phase 1, and correct anticipatory looks during Phase 2. See Tables 6-2 through 6-4 for full statistics.

Vocabulary comprehension. The first set of analyses focused on the CDI-1 vocabulary comprehension score (see Table 6-2). There were 17 infants with sufficient data to be included in these analyses. In the analysis of RT difference score, the average predicted initial vocabulary comprehension score was 31.7 words ($\beta_{00} = 31.72, p = .092$). The average growth in vocabulary comprehension score (per month of cochlear implant use) was 7.9 words, which was significantly more than zero ($\beta_{10} = 7.94, p = .012$). Infants' vocabulary comprehension slope did not significantly vary as a function of RT difference score ($\beta_{11} = 7.39, p = .340$).

In the analysis of correct anticipatory looks during Phase 1 the average predicted initial vocabulary comprehension score was 32 words and the average growth in vocabulary comprehension score (per month of cochlear implant use) was 8.8 words, which was significantly more than zero. Infants' vocabulary comprehension slope did not significantly vary as a function of correct anticipatory looks during Phase 1.

In the analysis of correct anticipatory looks during Phase 2 the average predicted initial vocabulary comprehension score was 32.2 words and the average growth in vocabulary comprehension score (per month of cochlear implant use) was 3.7words, which was not significantly more than zero. Infants' vocabulary comprehension slope did not significantly vary as a function of correct anticipatory looks during Phase 2. These results suggest that, in this small sample of infants, their performance on the VSL task was not related to growth in their vocabulary comprehension over the first 18 months of cochlear implant use.

Gestures score. The second set of analyses focused on the CDI-1 total gestures score (see Table 6-3). There were 17 infants with sufficient data to be included in these analyses. In the analysis of RT difference score the average predicted initial gestures score was 38.3. The average growth in gesture score (per month of cochlear implant use) was 1.6. Infants' gestural communication slope did not significantly vary as a function of RT difference score.

In the analysis of correct anticipatory looks during Phase 1 the average predicted initial gestures score was 37.9. The average growth in gesture score (per month of cochlear implant use) was 1.6. Infants' gestural communication slope did not significantly vary as a function of correct anticipatory looks during Phase 1.

In the analysis of correct anticipatory looks during Phase 2 the average predicted initial gestures score was 37.9. The average growth in gesture score (per month of cochlear implant use) was 1.8. Infants' gestural communication slope did not significantly vary as a function of correct anticipatory looks during Phase 2. These results suggest that, in this small sample of infants, performance on the VSL task was not related to growth in gesture comprehension during the first 18 months of cochlear implant use.

Vocabulary production. The final set of analyses focused on the CDI-2 vocabulary production score (see Table 6-4). There were only 5 infants with sufficient data to be included in these analyses, so these are preliminary results. In the analysis of RT difference score the average predicted initial vocabulary production score was 4.9 words and the average growth in vocabulary production score (per month of cochlear implant use) was 3.8 words, neither of which was significantly different from zero. Infants' vocabulary production slope did significantly vary as a function of RT difference score.

In the analysis of correct anticipatory looks during Phase 1 the average predicted initial vocabulary production score was 17 words and the average growth in vocabulary production score (per month of cochlear implant use) was 5 words, neither of which was significantly different from zero. In addition, infants' vocabulary production slope did not significantly vary as a function of correct anticipatory looks during Phase 1.

In the analysis of correct anticipatory looks during Phase 2 the average predicted initial vocabulary production score was -3.8 words and the average growth in vocabulary production score (per month of cochlear implant use) was -4.8 words, neither of which was significantly different from zero. Infants' vocabulary production slope did significantly vary as a function of correct anticipatory looks during Phase 2. These results suggest that there may be a relation between performance on the VSL task prior to cochlear implantation and growth in productive vocabulary during the first 18 months of cochlear implant use. However, due to the very small sample, more data are needed.

The VRM Task. On the VRM task we considered two different dependent variables: the novelty score across the two span-2 test trials and the novelty score across the three span-3 test trials. See Tables 6-5 through 6-7 for full statistics.

Vocabulary comprehension. The first set of analyses focused on the CDI-1 vocabulary comprehension score (see Table 6-5). There were 12 infants with sufficient data to be included in these analyses. In the analysis of span-2 novelty score, the average predicted initial vocabulary comprehension score was 52 words (β_{00} = 51.99, p = .016) and the average growth in vocabulary comprehension score (per month of cochlear implant use) was 8.8 words, which was not statistically different from zero (β_{10} = 8.83, p = .169). Infants' vocabulary comprehension slope did not significantly vary as a function of span-2 novelty score (β_{11} = -5.58, p = .615).

In the analysis of span-3 novelty score, the average predicted initial vocabulary comprehension score was 52 words and the average growth in vocabulary comprehension score (per month of cochlear implant use) was 21 words, which was a significant increase. Infants' vocabulary comprehension slope marginally varied as a function of span-3 novelty score. These results suggest that there may be a relation between performance on the VRM task prior to cochlear implantation and growth in receptive vocabulary during the first 18 months of cochlear implant use, but much more data are needed.

Gestures score. The second set of analyses focused on the CDI-1 total gestures score (see Table 6-6). There were 12 infants with sufficient data to be included in these analyses. In the analysis of span-2 novelty score the average predicted initial gestures score was 38.5 and the average growth in gesture score (per month of cochlear implant use) was 2.6. In addition, infants' gestural communication slope significantly varied as a function of span-2 novelty score.

In the analysis of span-3 novelty score the average predicted initial gestures score was 38 and the average growth in gesture score (per month of cochlear implant use) was 1, which was not significantly different from zero. Infants' gestural communication slope did not significantly vary as a function of span-3 novelty score. These results suggest that there may be a relation between performance on the VRM task prior to cochlear implantation and growth in gestural communication during the first 18 months of cochlear implant use, but more data are needed to make any strong claims.

Vocabulary production. The final set of analyses focused on the CDI-2 vocabulary production score (see Table 6-7), although there were only 3 infants with sufficient data to be included in these analyses. In the analysis of span-2 novelty score the average predicted initial vocabulary production score (after ~4 months of cochlear implant use) was 98.9 words. The average growth in vocabulary production score (per month of cochlear implant use) was -9 words. Infants' vocabulary production slope did not significantly vary as a function of span-2 novelty score.

In the analysis of span-3 novelty score the average predicted initial vocabulary production score was 120.7 words and the average growth in vocabulary production score (per month of cochlear implant use) was 7.8 words. Infants' vocabulary production slope did not significantly vary as a function of span-3 novelty score. The very small sample in these analyses preclude me from making any generalizations, but the current data suggest that there may not be a relation between performance on the VRM task prior to cochlear implantation and growth in productive vocabulary during the first 18 months of cochlear implant use.

Table 6-5

Results from the Growth Curve Analyses between the VRM Task and CDI-1 Vocabulary Comprehension Score

	Span-2 Novelty Score			**Span-3 Novelty Score**		
Parameter	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**
Fixed Effect						
Intercept (β_{00})	51.99	18.66	.016	51.83	18.32	.015
Months slope (β_{10})	8.83	5.99	.169	21.07	7.80	.021
VRM DV (β_{11})	-5.58	10.79	.615	-28.97	13.99	.063
Level-1 variance (σ^2)	2655.03			2634.83		
Intercept variance (τ_{00})	2932.63			2801.02		

Table 6-6

Results from the Growth Curve Analyses between the VRM Task and CDI-1 Total Gestures Score

	Span-2 Novelty Score			Span-3 Novelty Score		
Parameter	**Parameter Estimate**	**SE**	***p* value**	**Parameter Estimate**	**SE**	***p* value**
Fixed Effect						
Intercept (β_{00})	38.47	3.81	< .001	38.44	3.84	< .001
Months slope (β_{10})	2.59	0.38	< .001	1.05	1.14	.377
VRM DV (β_{11})	-2.49	0.57	.001	1.00	2.01	.628
Level-1 variance (σ^2)	12.49			11.85		
Intercept variance (τ_{00})	179.15			178.04		

Table 6-7

Results from the Growth Curve Analyses between the VRM Task and CDI-2 Vocabulary Production Score

	Span-2 Novelty Score			**Span-3 Novelty Score**		
	Parameter			**Parameter**		
Parameter	**Estimate**	**SE**	***p* value**	**Estimate**	**SE**	***p* value**
Fixed Effect						
Intercept (β_{00})	98.92	22.30	.021	120.74	30.18	.028
Months slope (β_{10})	-9.17	1.97	.043	7.75	12.21	.590
VRM DV (β_{11})	14.81	3.82	.061	-26.68	29.47	.461
Level-1 variance (σ^2)	533.35			680.79		
Intercept variance (τ_{00})	2.03			38.29		

Discussion

The results from this study suggest that there may be some relation between pre-implant performance on the VSL and VRM tasks and spoken language development during the first 18 months of cochlear implant use. Some of the relationships were in the predicted direction—we expected positive relations between the RT difference score and the slope in the VSL analyses; we expected positive relations between the novelty score and the slope in the VRM analyses. Unfortunately this is a small sample so more data are needed. In a larger sample, significant relations between VSL and/or VRM task performance with the CDI measures in deaf infants would support previous research suggesting a strong link between verbal and nonverbal abilities. The lack of significant relations would suggest that these nonverbal cognitive skills (visual sequence learning and visual recognition memory) may not be critical for spoken language development in this population.

CHAPTER VII

GENERAL DISCUSSION

This dissertation project is one part of a bigger project aimed at delineating the factors underlying the variability in spoken language outcomes in deaf children who use cochlear implants. The key to mitigating negative relations between deafness and children's spoken language development is to identify early predictors of language and use those predictors to refer children for early intervention. Given the importance of early intervention for children's outcomes, this dissertation aimed to discover whether there are nonverbal cognitive predictors of language ability for deaf children with cochlear implants that could be used identify those children most at risk for language difficulties (and subsequent educational failure).

First, the studies that make up this dissertation aimed to determine whether early deafness is related to children's nonverbal cognitive abilities; specifically contrasting their visual sequence learning and visual recognition memory to those of a group of same-aged hearing infants. Second, the current collection of studies aimed to determine whether visual sequence learning and visual recognition memory can provide predictive information about spoken language development in normal-hearing 8.5-month-olds and deaf infants who use cochlear implants. These goals were addressed through 5 specific research questions, which are detailed in the following section.

Specific Research Questions Revisited

The current dissertation addresses 5 specific research questions using the Visual Sequence Learning (VSL) and Visual Recognition Memory (VRM) tasks described in detail in Chapter II. Each research question is listed below, along with a description of how it was addressed. Each research question was addressed by a study, which was written in manuscript format in a separate chapter – Chapters III–VI. Research questions 2 and 3 addressed the potential link between nonverbal cognitive performance in infancy and spoken language outcomes for infants with normal hearing ability. Research questions 4 and 5 addressed the potential link between nonverbal cognitive ability in infancy and spoken language outcomes for deaf infants who use cochlear implants.

1. *Is early deafness related to nonverbal cognitive abilities in deaf infants? Specifically, do children who have experienced early auditory and language deprivation (as deaf infants prior to cochlear implantation) have deficits in implicit visual sequence learning or visual recognition memory? (Chapter III)*

In order to test whether deafness is related to nonverbal cognitive ability, deaf infants were tested on two nonverbal cognitive tasks: the VSL and the VRM. Their performance on the tasks was compared to hearing infants who were matched to them on chronological age. The hypothesis was that if deafness is related to general cognitive ability as assessed by a visual task, then the deaf infants might not be able to succeed on the VSL and VRM tasks at the same chronological ages as normal-hearing children. However, if deafness is not related to general cognitive ability, then the deaf infants should perform similar to same-aged hearing infants on the VSL and VRM tasks.

The groups did not perform statistically differently on the VSL task (n = 19) or the VRM task (n = 13). These results are inconclusive due to the relatively small sample sizes in the two studies, but even with a larger sample there may prove to be no group differences on these two tasks. One possible explanation for such a pattern of results is that these two visual tasks (VSL and VRM) might tap into learning processes that are not related to early deafness. Interestingly, the same-aged hearing infants did not demonstrate learning as a group on either the VSL or the VRM tasks, although many individual infants did demonstrate learning. This pattern of results is similar to the results from a study of normal-hearing infants aged 8.5 months (see Chapter IV and Shafto et al., 2012).

2. *Does sequence learning, as a domain-general process, relate to spoken language development in a group of infants with typical hearing ability? (Chapter IV)*

Chapter IV presents an investigation of the relation between early language development and performance on the VSL task as a test of domain-generality in language acquisition. Contrary to expectations, 8.5-month-old hearing infants did not demonstrate learning of the spatiotemporal sequence as a group. Correlational analyses were run between infants' performance on the VSL task and reported CDI vocabulary and grammatical measures at later ages (up to 30 months old). Infants who demonstrated learning of the sequence tended to have higher receptive vocabulary ability at testing and at follow-up at 13.5 months. At the later follow-up time points (17.5, 23.5, and 28.5 months), VSL performance was not significantly related to productive vocabulary ability.

I anticipated that there would be a positive correlation between the ability to learn a spatiotemporal sequence (performance on the VSL task) and early grammatical ability (e.g., the consistent use of regular inflectional morphology; for example, adding '-ed' for past tense). These analyses yielded an interesting pattern of results. There was not a significant correlation between VSL performance and grammatical ability at 23.5 months old, but there was a significant negative correlation between VSL performance and the use of over-regulars at 28.5 months. There were also marginal negative correlations between VSL performance and the use of inflection and irregular words at 28.5 months.

Therefore, performance on the VSL task was significantly correlated with both CDI vocabulary and grammatical ability, but it accounted for different amounts of variability and emerged at different time points. This pattern of results could reflect individual differences in language development.

3. Is visual recognition memory a significant correlate of early language development in a group of infants with typical hearing ability? (Chapter V)

Chapter V presents an investigation of the relation between early language development and performance on the VRM task as a test of domain-generality in language acquisition. Contrary to findings by Rose and colleagues, the normal-hearing 8.5-month-old infants did not demonstrate a group pattern of recognition memory. Correlations were run between infants' performance on the VRM task and reported CDI vocabulary and grammatical measures at later ages (up to 30 months old). I expected to replicate previous research by finding a positive correlation between visual recognition performance at approximately 8.5 months old and English productive vocabulary as a toddler. However, a pattern of negative correlations was found instead. There were also significant negative correlations between VRM performance and inflection use at 23.5 months and irregular word production at 28.5 months. This pattern of results suggests that this VRM task was not ideally set up (i.e., does not measure recognition memory in the same manner as previous studies). Alternatively, it could be that the worst performers actually habituated to the task because they are faster processors. A version of the VRM that included a long-term retention measure would clarify whether that happened because one would expect better long-term retention if those infants were actually better information processors.

4. Does performance on a visual sequence learning task relate to spoken language ability in deaf infants? (Chapter VI)

The fourth research question aimed to determine the relation between VSL task performance during infancy and spoken language ability after up to 18 months of cochlear implant use in deaf infants. The deaf infants' performance on the VSL task was tested as a predictor of their reported language growth in a growth curve analysis.

The results suggest that, in the current sample of infants, performance on the VSL task prior to implantation was not related to growth in receptive vocabulary or gestural ability over the first 18 months of cochlear implant use, but may be related to productive vocabulary. If this pattern of results held up for a larger group of infants, this would suggest that the nonverbal cognitive ability tapped in the VSL task is not critical for at least some aspects of spoken language development in deaf children who use cochlear implants, and that potential deficits in nonverbal cognitive ability are not necessarily associated with poorer spoken language ability in deaf infants who use cochlear implants.

5. Does performance on a visual recognition memory task relate to spoken language ability in deaf infants? (Chapter VI)

The fifth research question, in conjunction with research question 4, aimed to determine the relation between nonverbal ability (in this case, VRM task performance) during infancy and spoken language ability after up to 18 months of cochlear implant use in deaf infants. The deaf infants' performance on the VRM task was tested as a predictor of their reported language growth in a growth curve analysis. The results from this small sample suggest that performance on the VRM task prior to cochlear implantation may be related to growth in receptive vocabulary and gestural ability over the first 18 months of cochlear implant use. If this pattern of results held up for a larger group of infants, this would suggest similarities to hearing children with regard to the cognitive underpinnings of language (e.g., Plomin & Dale, 2000 and Chapter III).

The Correlation between VSL Performance and Receptive Vocabulary

There are several possible explanations for why the normal-hearing infants' performance on the VSL task is correlated with their receptive vocabulary ability. One is that procedural learning itself (a general learning process) – rather than some general cognitive process such as attention – is used to learn language. Indeed, the possibility that there is a relationship between procedural processes and language learning is supported by recent theories of language acquisition that posit an important role for non-declarative, or procedural memory, in language development (Ullman, 2004) and by neuropsychological evidence showing that procedural memory deficits result in language problems (Ullman, 2001; Ullman et al., 1997; Ullman et al., 2005). Also, previous research on sequence learning has established that it is correlated with language processing in adults (Conway et al., 2010; Misyak, Christiansen, & Tomblin, 2010) and hearing-impaired children (Conway, Pisoni, et al., 2011), as well as English passive production in typically-developing hearing children (Kidd, 2012).

On the other hand, it is possible that some other factor, such as information processing speed, is responsible both for normal-hearing infants' performance on the VSL task and on their receptive language ability. In order to determine the contribution of VSL specifically, future work would need to include measures of other cognitive skills that could be partialled out in the analyses. This approach was used by Rose and colleagues (Rose, Feldman, Jankowski, & VanRossem, 2005) who used structural equation modeling to determine which of a series of information processing skills mediated cognitive development. However, that study did not include any procedural or sequential learning measures. The results of the current study suggest that future work should also include these types of learning measures. In addition, future studies should examine various components of language development (e.g., vocabulary vs. syntax) rather than using a single measure as a proxy for 'language'.

The Correlation between VSL Performance and Productive Grammar

There are several possible explanations for why normal-hearing infants' performance on the VSL task at 8.5 months is *negatively* correlated with their productive grammatical ability at 23.5 and 28.5 months old. One possibility is that infants are learning the sequence earlier in the experiment (i.e., during Phase 1), which leads to a slowdown in RT once they get bored (i.e., during Phase 2). However, the positive correlation between our measure of learning—which is based on the reduction in RT from Phase 1 to Phase 2—and receptive language ability at 8.5 and 13.5 months, as well as the differences in receptive language ability between infants who demonstrated learning and those who did not, suggest that this is not the case.

A second possibility relates to development on these grammatical measures within a particular child over time. Specifically, the fact that a child is over-regularizing could mean s/he is advanced at an early age, but at a later age it could indicate that s/he is lagging developmentally (since all children eventually stop over-regularizing). Unfortunately this possibility cannot be investigated with the current data set, because the children weren't sampled frequently enough to know exactly when they started and stopped over-regularizing.

A third possibility is that this measure of sequence learning (VSL performance) actually measures declarative and not procedural learning. If this were a measure of declarative learning, one would expect performance on the task to correlate with vocabulary ability (see Ullman, 2004). If the procedural and declarative learning systems work competitively (e.g., the better one is at declarative, the worse one is at procedural, etc.), then that might explain the negative correlation between VSL performance and the measures of grammatical ability later in development. This possibility is unlikely because, in general, children who have better vocabulary skills also have better grammar skills, a pattern which was also found in the current sample (Table 4-9). Instead, it could be that infants who rely more on declarative memory show early advantages in vocabulary acquisition and early disadvantages in grammatical acquisition, but later on the two language abilities begin to correlate more positively because they feed off each other (i.e., semantic and grammatical bootstrapping).

Finally, an additional analysis may shed light on this interesting pattern of results. Not all of the normal-hearing infants had CDI data available at all of the follow-up time points, so there is actually a slightly different group of children represented in each follow-up CDI time point (unlike in a truly longitudinal design). Therefore data were analyzed for only the children who had reported CDI-2 scores at 23.5 months ($n = 39$). This subgroup had negative correlations between VSL performance and measures of CDI-2 grammar, but the same children do not show the positive correlation between VSL performance and CDI-1 receptive vocabulary at 8.5 or 13.5 months. This suggests that, by chance, the parents who filled out the later CDI-2s had children who, as a group, do not show the original positive correlation with receptive vocabulary. It is therefore not the case that normal-hearing infants who show a positive correlation between VSL task performance and early receptive vocabulary at 8.5 or 13.5 months old later show a negative correlation between VSL task performance and early grammatical ability. Thus it is possible that the negative correlations are spurious and would be nonsignificant in a larger sample of hearing children aged 23.5 and 28.5 months old, or in a sample in which every child had a CDI for every time point.

Domain-Generality and Modality-Specificity

Current theories suggest that sequence learning may contribute to language acquisition because the latter is an unconscious developmental process (Cleeremans, Destrebecqz, & Boyer, 1998) that appears to involve brain areas associated with procedural memory (Ullman, 2001). Because people often use language without an explicit understanding of the rules of grammar dictating its structure, it is likely that much knowledge of language is gained through implicit learning processes such as sequence learning (Cleeremans et al., 1998). If these processes are important for language development, early performance on such tasks could be used for predicting language outcomes from a very young age.

It is important to note that some of the significant correlations found in the current study – between sequence learning and vocabulary comprehension in normal-hearing infants – involved skills that do not share learning modality. Specifically, the VSL task involved the use of visual-motor skills, while vocabulary comprehension involves the use of audition. The other CDI-1 correlation – between visual sequence learning performance and gestural ability 5 months after performing the VSL task – involved skills in the same modality (both are visual-motor). This pattern of results suggests that sequence learning and language learning share some domain-general processes.

Behavioral evidence suggests that statistical sequential learning is constrained by the sense modality in which the input patterns occur, with auditory learning proceeding in substantially different ways compared to visual or tactile learning. In particular, in a study with tactile, auditory, and visual sequential learning tasks, adults were better at learning auditory sequences compared to the other two modalities (Conway & Christiansen, 2005; Emberson et al., 2011). Furthermore, there are qualitative differences in learning across the modalities, with each modality being differentially biased toward the beginning or final elements of a sequence (Conway & Christiansen, 2005). This behavioral evidence is supported by neuroimaging data showing that implicit learning is largely mediated by modality-specific unimodal processing mechanisms (Keele et al., 2003; Turk-Browne et al., 2009). Yet on the other hand, learning also appears to be domain-general in the sense that performance on a visual task was significantly correlated with performance on a measure of spoken language perception using auditory stimuli (Conway et al., 2010). In terms of neural processes, implicit learning is known to involve supramodal brain regions, or regions that are unrestricted with regard to modality, such as the prefrontal cortex and basal ganglia (Bapi, Chandrasekhar Pammi, Miyapuram, & Ahmed, 2005; Clegg et al., 1998)—areas also used for language processing.

Importantly, this same combination of domain-generality and modality-specificity appears to also characterize language. For instance, both reading and listening tasks involve a common phonological network of brain regions, including the inferior frontal area, whereas visual and auditory unimodal and association areas are preferentially active during reading and listening tasks, respectively (Jobard et al., 2007). This combination of domain-generality and modality-specificity in sequence learning and language may therefore explain the correlation between VSL task performance and the gesture comprehension score. Because VSL relies to some extent on the same domain-general learning processes used for language processing, it is associated with global measures of language development, regardless of the domain (i.e., spoken vocabulary comprehension). On the other hand, because VSL also involves modality-specific processes for learning the visual-motor sequential patterns, VSL appears to be useful for predicting aspects of visual-motor communication later in development; specifically, the comprehension of gesture. To our knowledge, this is the first evidence showing that sequence learning and language development share some domain-general processes.

The Role of Domain-General Processes in Language

In either case, the current findings support the idea that domain-general cognitive processes are important for language development. As discussed, there is already evidence for a positive relation between visual recognition memory and cognitive and linguistic outcomes (Colombo et al., 2004; Fagan & McGrath, 1981; Rose & Feldman, 1997; Rose et al., 2009; Rose et al., 1991). In addition, studies on infant habituation rate and novelty preference have demonstrated a link between attention and cognitive outcomes, including language (Colombo et al., 2004; Kannass & Oakes, 2008; McCall & Carriger, 1993; L. Thompson et al., 1991). Taken together, and in conjunction with findings from the current study, these findings suggest a positive relation between certain domain-general processes and language development.

Future Research

With a larger sample of deaf infants there are several patterns that could emerge. If there were significant differences between the normal-hearing and the deaf infants (matched on chronological age), meaning that the deaf infants have slower reaction times or are unable to learn the visual sequence in VSL and unable to recognize familiarized images in VRM, that would suggest that deafness is negatively related to general cognitive processes, at least in the two domains tapped through these experimental tasks. This pattern of results would be consistent with recent research suggesting general cognitive differences between deaf and hearing infants prior to spoken language acquisition (Shafto et al., under review). If the deaf and normal-hearing infants perform similarly on the two experimental tasks, this would suggest that deafness does not related to visual sequence learning and/or visual recognition memory. It is also possible that deaf infants would show a different pattern of performance compared to the hearing infants on only one of the two experimental tasks, such as poorer performance on the VSL task, but similar performance on the VRM task. That pattern of results would suggest that deafness only relates to some general cognitive processes – in this case, sequence learning. This would be consistent with Conway, Pisoni, and Kronenberger's (2009) proposal that experience with sound provides a necessary scaffold for learning sequential or temporal patterns. As another example, there is a growing body of research suggesting that memory may be impaired in children with severe hearing impairment (e.g. Burkholder & Pisoni, 2003, 2006; Pisoni & Cleary, 2003). If the deaf infants demonstrated poorer recognition memory compared to age-matched infants with normal hearing, that would suggest that differences in memory may emerge very early in development.

Summary

The goal of this series of studies was to investigate the relation between 2 non-verbal abilities (visual sequence learning and visual recognition memory) and language outcomes in infants. Finding early predictors of later language development could allow clinicians to better focus their early therapy strategies on cognitive and linguistic skills that are important for language development. The results of the current studies opens the door for future research on how different domain-general abilities are related to different aspects of language and the role that modality may play in this transfer process.

The studies with normal-hearing infants provide evidence for a significant relation between visual sequence learning and spoken language outcomes (Chapter IV). Specifically, it was found that sequence learning (thought to rely on procedural memory) may contribute to vocabulary and gestural development in normal-hearing infants. Further research with larger samples of children is needed to determine whether procedural learning may be important for grammar acquisition (see Ullman, 2004).

Results from the studies with deaf infants suggest that there is not a significant difference in visual sequence learning or visual recognition memory between deaf and hearing infants matched on chronological age (Chapter III) although the lack of group learning in either group makes this difficult to ascertain. In addition, results from these studies suggest that visual sequence learning may not be related to spoken language outcomes for deaf infants who use cochlear implants, although visual recognition memory may be (Chapter VI). Recruiting a larger sample of deaf infants is necessary to clarify whether nonverbal cognitive skills are related to early deafness, and how those skills might relate to spoken language development in this unique population.

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CURRICULUM VITAE

Carissa L. Shafto

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EDUCATION

University of Louisville, Louisville, KY (2007 – 2013)

- Ph.D. in Experimental Psychology (Cognitive & Developmental Sciences)
  - Advisor: Frederic L. Wightman, Ph.D.
  - Co-Advisor: Derek M. Houston, Ph.D. (Indiana University)
- M.S. in Experimental Psychology (Cognitive & Developmental Sciences), 2009

ICPSR, University of Michigan, Ann Arbor, MI (2011)

- Summer Program in Quantitative Methods of Social Research
  - Completed 4-week courses in longitudinal data analysis, advanced multivariate methods, missing data

Northeastern University, Boston, MA (2000 – 2003)

- B.A. in Psychology with honors, *magna cum laude*
- B.S. in Linguistics with honors, *magna cum laude*

RESEARCH INTERESTS

the effect of early experience on language and cognitive development; predicting language outcomes; the relation between verbal and nonverbal development; the role of maternal input and related factors (e.g., SES) on language development; using longitudinal statistical techniques to analyze trajectories and outcomes in education research

PUBLICATIONS

Journal Articles

Snedeker, J., Geren, J., & **Shafto, C. L.** (2012). Disentangling the effects of cognitive development and linguistic expertise: A longitudinal study of the acquisition of English in internationally-adopted children. *Cognitive Psychology, 65,* 39-76. DOI: 10.1016/j.cogpsych.2012.01.004.

Shafto, C. L., Conway, C. M., Field, S. L., & Houston, D. M. (2012). Visual sequence learning in infancy: Domain-general and domain-specific associations with language. *Infancy, 17,* 247-271. DOI: 10.1111/j.1532-7078.2011.00085.x.

Snedeker, J., Geren, J. & **Shafto, C. L.** (2007). Starting over: International adoption as a natural experiment in language development. *Psychological Science, 18*, 79-87. DOI: 10.1111/j.1467-9280.2007.01852.x.

Refereed Conference Proceedings & Book Chapters

Shafto, C. L. & Adelson, J. L. (2012). A random intercept regression model using HLM: Cohort analysis of a mathematics curriculum for mathematically promising students. In G. D. Garson (Ed.), *Hierarchical Linear Modeling: Guide and Applications* (pp. 167-182). Austin, TX: Sage Publications.

Shafto, C. L., Geren, J., & Snedeker, J. (2010). Effects of maternal input on language in the absence of genetic confounds: Vocabulary development in internationally adopted children. In S. Ohlsson & R. Catrambone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society.* Austin, TX: Cognitive Science Society.

GRANTS & FELLOWSHIPS AWARDED

- NIDCD NRSA Individual Predoctoral Fellowship F31 DC010281, ~$68,413 (Jan 2011 – Jun 2013)
  "Deaf infants' cognitive skills and their post-cochlear implant language outcomes"
- Psi Chi Graduate Research Grant, $960 (Aug 2010 – Oct 2012)
  "Auditory statistical learning ability in children with cochlear implants: Insight into the development of speech segmentation"
- University of Louisville, A & S Dean's Office, Graduate Student Research Award, $500 (May 2010)
  "Auditory statistical learning ability in children with cochlear implants: Insight into the development of speech segmentation"
- University of Louisville, A & S Graduate Student Union, Student Research Grant, $100 (Mar 2010)
  "Nonverbal cognitive ability of toddlers with cochlear implants: Investigating effects of auditory deprivation"

COMPETITIVE AWARDS & HONORS

Graduate

- CI2011 Travel Award to present at the Symposium on Cochlear Implants in Children (2011)
- SRCD Student Travel Award to present at the biennial meeting of the SRCD (2011)
- University of Louisville
  - *Arts & Sciences Graduate Student Union Research Award (Spring 2011 & 2012)*
  - *First Prize for Social Sciences oral presentation at the GSC Graduate Research Symposium (2010)*
  - *Arts & Sciences, Outstanding Master of Science Student in Experimental Psychology (2009)*
- Paula Menyuk Travel Award to present at BUCLD (2010)
- CI2009 Trainee Scholarship to present at the Symposium on Cochlear Implants in Children (2009)
- NIH Travel Award to present at the Symposium on Research in Child Language Disorders (2008)
- National Science Foundation Graduate Research Fellowship Program, Honorable Mention (2007)

Undergraduate

- Martin Luther King Scholarship (1999)
- Elks National Foundation State Scholarship (1999)

PRESENTATIONS

Refereed Conference Presentations

Shafto, C. L., Houston, D. M., & Bergeson, T. R. (2013, April). *Visual attention and habituation in deaf oral infants.* In **C. L. Shafto** (chair), Sensory and linguistic contributions to the development of attentional processes: Insights from deaf populations. Paper presented at the Society for Research in Child Development Biennial Meeting. Seattle, WA.

Houston, D. M., & **Shafto, C. L.**. (2013, April). *Deaf Infants' attention to speech after cochlear implantation: Effects of early experience.* In **C. L. Shafto** (chair), Sensory and linguistic contributions to the development of attentional processes: Insights from deaf populations. Paper presented at the Society for Research in Child Development Biennial Meeting. Seattle, WA.

Shafto, C. L., Houston, D. M., & Bergeson, T. R. (2012, June). *Slower visual habituation in deaf infants: Evidence for effects of auditory deprivation?* Poster presented at the XVIII Biennial International Conference on Infant Studies. Minneapolis, MN.

Shafto, C. L., Houston, D. M., & Bergeson, T. R. (2012, June). *Early sensory deprivation is associated with slower visual habituation in deaf infants.* Paper presented at the 42nd Annual Meeting of the Jean Piaget Society. Toronto, ON.

Snedeker, J., **Shafto, C. L.,** & Geren, J. (2011, July). *Divergent paths: Effects of age of arrival on course of language development in internationally-adopted children.* In Fred Genesee (chair), Language acquisition and development in internationally-adopted children. Paper presented at the XII International Congress for the Study of Child Language. Montréal, Québec.

Shafto, C. L., Houston, D. M., Bergeson, T. R., & Miyamoto, R. T. (2011, July). *Visual attention and encoding ability in deaf infants before and after cochlear implantation.* Poster presented at the Thirteenth Symposium on Cochlear Implants in Children, Chicago, IL.

Shafto, C. L., Conway, C. M., Field, S. L., & Houston, D. M. (2011, March). *Visual sequence learning in infancy: A domain-general predictor of vocabulary.* In **C. L. Shafto** & D. M. Houston (chairs), Maximizing the variance accounted for in language outcomes: Cognitive, linguistic, and attentional predictors. Paper presented at the Society for Research in Child Development Biennial Meeting. Montréal, Québec.

Shafto, C. L., Houston, D. M., Bergeson, T. R., & Miyamoto, R. T. (2011, March). *Visual attention and encoding ability in deaf infants before and after cochlear implantation.* Paper presented at the SRCD pre-conference on the development of deaf and hard of hearing children. Montréal, Québec.

Shafto, C. L., Conway, C. M., Field, S. L., & Houston, D. M. (2010, November). *Visual sequence learning in infancy: A domain-general predictor of vocabulary ability.* Paper presented at the Boston University Conference on Language Development. Boston, MA.

Shafto, C. L., Geren, J., & Snedeker, J. (2010, August). *Effects of maternal input on language in the absence of genetic confounds: Vocabulary development in internationally* *adopted children*. Paper presented at the annual meeting of the Cognitive Science Society. Portland, OR.

Shafto, C. L., Geren, J., & Snedeker, J. (2010, March). *Maternal input effects in the absence of genetic confounds: English vocabulary development in international adoptees*. Poster presented at the XVII Biennial International Conference on Infant Studies. Baltimore, MD.

Shafto, C. L., & Wightman, F. L. (2010, March, declined). *Meta-analysis of data on hearing impaired children's speech perception.* Accepted for presentation at the American Auditory Society Annual Meeting. Scottsdale, AZ.

Snedeker, J., Worek, A., & **Shafto, C. L.** (2009, November). *The role of lexical bias and global plausibility in children's online parsing: A developmental shift from bottom-up to top-down cues.* Paper presented at the Boston University Conference on Language Development. Boston, MA.

Shafto, C. L., Field, S. L., Conway, C. M., Tinter, S., & Houston, D. M. (2009, June). *Visual sequence learning in infancy: A predictor of later vocabulary?* Paper presented at the Twelfth Symposium on Cochlear Implants in Children, Seattle, WA.

Shafto, C. L., Geren, J., & Snedeker, J. (2008, July). *The pace of English language development in internationally adopted children: A role for cognitive ability, but not native language*. Poster presented at the XI International Congress for the Study of Child Language, Edinburgh, UK.

Shafto, C. L., Geren, J., & Mervis, C. B. (2008, June). *Language and literacy skills of children adopted from Eastern Europe: Effects of age of arrival in the United States*. Poster presented at the Symposium on Research in Child Language Disorders. Madison, WI.

Snedeker, J., Worek, A., & **Shafto, C. L.** (2008, March). *The role of plausibility in children's online language processing.* Poster presented at the CUNY Conference on Human Sentence Processing. Chapel Hill, NC.

Shafto, C. L., Geren, J., & Snedeker, J. (2007, March). *English language development and early literacy in internationally adopted children.* Poster presented at the Society for Research in Child Development Biennial Meeting. Boston, MA.

Geren, J., **Shafto, C. L.,** & Snedeker, J. (2007, March). *English acquisition in international adoptees mirrors first language learning.* Poster presented at the Society for Research in Child Development Biennial Meeting. Boston, MA.

Geren, J., **Kemp, C. L.,** & Snedeker, J. (2006, May). *Does L1 always influence acquisition of L2? Evidence from international adoption.* Poster presented at the Language Acquisition & Bilingualism Conference. Toronto, ON.

Kemp, C. L. & Snedeker, J. (2005, November). *Combining cross-situational and structural cues to verb meaning.* Paper presented at the Boston University Conference on Language Development. Boston, MA.

Symposia Chaired

Symposium Chair (2013, April): *Sensory and linguistic contributions to the development of attentional processes: Insights from deaf populations.* Symposium presented at the Society for Research in Child Development Biennial Meeting. Seattle, WA.

Symposium Chair (2011, March): *Maximizing the variance accounted for in language outcomes: Cognitive, linguistic, and attentional predictors*. Symposium presented at the Society for Research in Child Development Biennial Meeting. Montréal, Québec.

Invited Talks

Shafto, C. L. (2011, August). *Nonverbal cognitive skills in deaf infants.* Colloquium Series, DeVault Otologic Research Laboratory, Indiana University School of Medicine, Indianapolis, IN.

Shafto, C. L. (2010, August). *Visual sequence learning in normal-hearing and deaf infants: A predictor of vocabulary?* Grand Rounds, Heuser Hearing Institute, Louisville, KY.

Shafto, C. L. (2009, March). *Auditory statistical learning in children with normal hearing or cochlear implants.* DeVault Otologic Research Laboratory, Indiana University School of Medicine, Indianapolis, IN.

Media Coverage

Adoptees offer clues on skills of language: Harvard research uncovers pattern
Research featured February 15, 2010 in the Boston Globe.
http://www.boston.com/news/science/articles/2010/02/15/children_adopted_from_abroad_offer_insight_on_language_development/

Why don't babies talk like adults? Going from "goo-goo" to garrulous one step at a time.
Research featured February 3, 2009 in Scientific American.
http://www.sciam.com/article.cfm?id=babies-talk-language-development

TEACHING

Graduate

University of Louisville, Educational and Counseling Psychology Department
Louisville, KY

Guest Lecturer: Hierarchical Linear Models (Spring 2011 & 2012); Structural Equation Modeling (Fall 2011)

Graduate Teaching Assistant: Hierarchical Linear Models (7 PhD students, Spring 2011)

- Assisted with in-class lab activities, met with students one-on-one for assistance doing multi-level models (including growth curve modeling), graded weekly homework assignments

Undergraduate

Indiana University Southeast, School of Social Sciences
New Albany, IN

Adjunct Faculty Instructor: Intro to Psychology (Spring 2013)

- Wrote and delivered all lectures, created in-class activities and writing assignments, met with students one-on-one for writing assistance, graded all assignments

University of Louisville, Department of Psychological and Brain Sciences
Louisville, KY

Adjunct Faculty Instructor: Cognitive Processes (Summer 2012)

- Wrote and delivered all lectures, created in-class activities and writing assignments, met with students one-on-one for writing assistance, graded all assignments

Lab Instructor: Experimental Psychology Lab Sections (i.e., Research Methods; Spring 2010)

- Wrote and delivered all lab lectures, created in-class lab activities, met with students one-on-one for writing assistance, graded weekly writing assignments and final paper (a full-length APA-style research paper)

Guest Lecturer: Experimental Psychology (Spring 2010), Cognitive Processes (Fall 2009)

Graduate Teaching Assistant: Experimental Psychology (Spring 2010), Cognitive Processes (Fall 2009), Lifespan Development (Spring & Fall 2008, Spring 2009)

Harvard University, Psychology Department
Cambridge, MA

Co-supervisor: Independent Research (Spring 2005)

Mentor: Lab for Developmental Studies Summer Internship Program (Summers 04 – 06)

LAB MANAGEMENT EXPERIENCE

Harvard University Psychology Department, Cambridge, MA (Jun 04 – Jun 07)
Lab Coordinator/Research Assistant, Laboratory for Developmental Studies
Advisor: Jesse Snedeker, Ph.D.

Northeastern University Psychology Department, Boston, MA (Nov 03 – Aug 04)
Lab Coordinator/Research Assistant, Categorization and Reasoning Laboratory
Advisor: John D. Coley, Ph.D.

PROFESSIONAL SERVICE

Ad-Hoc Journal Reviewing
Language Learning & Development (2012 – present)

Conference Reviewing
Cognitive Science Society (2010 – present)

Arts & Sciences Graduate Student Union, University of Louisville
Vice President (2010 – 2012)
Experimental Psychology Program Representative (2009 – 2010)

Experimental Psychology Seminar Series, University of Louisville
Founder 2008
Organizer (2008 – 2011)

Experimental Psychology Graduate Program, University of Louisville
Graduate Student Representative (2008 – 2011)

Professional Memberships
Cognitive Development Society, Psi Chi, International Society for Infant Studies, American Psychological Association, American Association for the Advancement of Science, Society for Research in Child Development, Cognitive Science Society

STATISTICS, COMPUTER & LANGUAGE SKILLS

- Advanced statistics courses: *longitudinal data analysis, meta-analysis, multi-level modeling (organizational and longitudinal), multivariate statistics, structural equation modeling*
- Statistical software competence: *AMOS, Comprehensive Meta-Analysis, HLM, R, SPSS*
- Computer programming: *MATLAB, R*
- Digital audio and video editing software: *Adobe Audition/CoolEdit, AVID*
- Foreign languages: *Intermediate Polish; Basic Spanish; Survival French*