Exploring the Relationship between Sequence Learning, Motor Coordination, and Language Development

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The Graduate Center, City University of New York
EXPLORING THE RELATIONSHIP BETWEEN SEQUENCE LEARNING, MOTOR COORDINATION, AND LANGUAGE DEVELOPMENT

by

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ABSTRACT

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Dual-route approaches to language acquisition posit separable mechanisms for acquisition of vocabulary and grammar (e.g., Pinker, 1998). Working within the dualistic framework, Ullman and Pierpont (2005) proposed the procedural deficit hypothesis, which proposes that impairments in rule-based aspects of language (e.g. grammar, phonology) observed in children with Specific Language Impairment (SLI) may be linked to neural deficits that govern procedural memory and are critical for the procedural/sequence learning of both, cognitive and motor skills. In support of this hypothesis, recent meta-analyses indicate significant deficits in sequence learning in children with SLI relative to controls (Lum et al., 2014). Further research has found deficits in nonword repetition among children who are language impaired. Nonword repetition has also been associated with children's vocabulary development (Gathercole & Baddeley, 1990) suggesting that while nonword repetition is hypothesized to be procedural in nature, it is highly associated with children's word learning, which is thought to be learned declaratively.

In contrast to the dual-route framework, which has received more attention in the more recent years, single-route approaches to language development view vocabulary and grammar learning as fundamentally interconnected, as supported by very high correlations between measures of vocabulary diversity and grammatical complexity (e.g., mean utterance length) at all
stages of development. This idea that all aspects of language are interrelated emerges from domain-general theories of child development and extends beyond language by suggesting that links exist between children’s language, motor, and cognitive development (Bates & Dick, 2000; Iverson & Thelen, 1999). This approach is supported by neurodevelopmental research (Diamond, 2000), in addition to research showing that children with language impairments also show difficulties in motor control. In line with this view, researchers have been pushing for a unification between the fields of motor and language development (Iverson, 2010).

The majority of the literature that has found support for the dual-route hypothesis has used extreme-group design to examine differences between clinical and typically developing populations. In this study, we use an individual differences approach to examine the role of sequence learning and motor coordination (fine motor coordination in particular) in language development in a community sample of school ages children. We administered a battery of language and cognitive assessments to a diverse community sample of 63 children (33 girls, 30 boys), mean age 8 years; 2 months (SD 1;3). We employed a commonly used measure of sequence learning (the Serial Reaction Time task) in addition to the pegboard task to examine motor coordination and the nonword repetition task to examine phonology. Results showed that while controlling for age and nonverbal working memory, using the traditional measures of sequence learning, we were unable to find a relationship with any measure of language, this finding was in line with some of the individual differences research in the field (Lum & Kidd, 2012) but not with group-level research looking at sequence learning between SLI and typically developing children. On the other hand, measures of motor coordination (as measured using the pegboard task) were related to individual differences in all aspects of language, including vocabulary, grammar, and phonology. Furthermore, all language measures were correlated with
one another. In attempts to replicate these findings, we found associations between motor coordination (measured using accuracy on Block 1 of the SRT task) and measures of vocabulary and grammar. Post-hoc analyses also showed that nonverbal intelligence was also associated with performance on the pegboard task. These results implicate fine motor coordination as a factor contributing to variance in language and cognitive abilities, but fail to support the view that word-based (vocabulary) and rule-based (grammar and phonology) aspects of language are different and possibly acquired via separable mechanisms. Our findings are in line with domain-general approaches to development which discuss the relationships between both verbal and motor abilities in children, suggesting that these two developmental areas are largely intertwined (Thelen, 2010).

**Keywords:** motor coordination, sequence learning, language development, individual differences
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CHAPTER 1

Introduction

Theories of Language Acquisition: Dual versus Single Routes of Language Understanding

Theories of language development have been generally categorized under two common theories: single versus dual routes of language acquisition. Dual-route approaches to language acquisition suggest that distinct mechanisms are responsible for the acquisition of words (e.g. vocabulary) and rules (e.g., grammar and phonology) in children. Conversely, single route theories suggest that all aspects of language development (e.g. vocabulary, grammar, and phonology) co-occur together and are highly interrelated. In line with the dualistic view of language acquisition, Steven Pinker (Pinker, 1991; 1998) theorizes that the acquisition of different aspects of language (e.g. vocabulary versus grammar) occur according to different processing substrates. Working within this framework, researchers have suggested that knowing the rules of word order in language (grammar) and the rules of the sound order in language (phonology) occur within the procedural memory system, which is responsible for rule-based aspects of learning, however, word-knowledge (i.e. vocabulary) is instead governed by the declarative memory system, which is responsible for our knowledge of facts (Ullman et al., 1997; Ullman, 2004).

In line with the single-route approach to language development, Bates and her colleagues (Bates, Thal, Finlay, Clancy, 1992; Bates, Dale, & Thal, 1995; Bates & Goodman; 1997) have argued that the development of grammar and vocabulary is in fact inseparable in child development. These findings were supported by high correlations between individuals' vocabulary diversity and grammatical complexity at all stages of development. The authors
concluded that relationships between lexical and grammatical development rely on a *unified lexical processor* for language learning.

The single processing theory has been historically more accepted, in light of domain-general views of child development, but in the past few decades there has been a discussion in the literature of how memory systems (procedural/declarative) apply to language learning, and whether the divisions in memory systems have a parallel division in language processing. According to Pinker’s theory, the learning of rule-based aspects of language, such as grammar and phonology, occurs in the procedural memory system, which has been commonly associated with skill acquisition. Conversely, word learning occurs in the declarative memory system that is related to the learning of factual information (e.g., our knowledge that the world is round). However, since not all researchers seem to concur that language learning occurs based on two separate routes of processing, and because the literature in support of the dualistic view on language development remains mixed, we set out to explore the plausibility of this controversial claim by adopting an individual differences approach to examining the role of procedural/sequence learning in relation to various aspects of children’s language and cognitive skills (Note: throughout this dissertation individual differences is defined as a range of values observed in various predictor and outcome measures, such as language abilities, sequence learning, and motor skills).

**The Procedural Deficit Hypothesis**

The procedural deficit hypothesis (PDH; Ullman & Pierpont, 2005) argues that procedural and declarative memory systems underlie a division in language development. Since this theory was derived from the declarative/procedural model of memory (Ullman, 2004), it
suggests that the learning of word meanings (e.g. vocabulary) occurs in the declarative memory system in the temporal-lobes areas of the brain that underlie factual knowledge. Conversely, learning the rules of language (e.g. grammar) depends on neural networks that underlie procedural memory. The PDH thus suggests that challenges with rule-based aspects of language, such as difficulties with grammar and phonology, may be linked to neural deficits that govern procedural memory and are critical for the sequence learning of language, cognitive, and motor skills (Frith & Frith, 2008; Perruchet & Pacton, 2006; Romberg & Saffran, 2010; Ruffman, Taumoepeau, & Perkins, 2012). Ullman (Ullman & Pierpont, 2005; Ullman, 2004) explains that since children with Specific Language Impairment (SLI) mostly show difficulties in grammatical areas of language development, including syntax (van der Lely & Stollwerck, 1996) and phonology (Gathercole & Baddeley, 2014), Ullman posits that deficits in the procedural system leads to dysfunction in both motor learning and rule-based language learning. This hypothesis has gained great recognition because it attempts to explain language delay in relation to a deficit in procedural learning, assigning a possible causal root that could be used as a theoretical underpinning for interventions.

After the publication of the procedural deficit hypothesis in 2005, researchers became increasingly interested in examining deficits in sequence learning as possible underlying impairments in SLI (e.g., Tomblin, Mainela-Arnold, & Zhang, 2008). In line with the PDH, deficits in sequence learning have been implicated in a range of developmental disorders, such as Specific Language Impairment (SLI, for meta-analysis see Lum, Conti-Ramsden, Morgan, & Ullman, 2014) and Dyslexia (Lum, Ullman, & Conti-Ramsden, 2013). Sequence learning involves our abilities to learn difficult and complex sequences in the environment without direct learning and instruction. Sequence learning is defined as the “detection of patterns of covariation
between elements in complex stimulus domains” (Reber, 2015, pp. viii), in other words it is the ability to detect complex rules or patterns in the environment without awareness. The literature alternates between the terms implicit, statistical, sequence, and procedural learning (see Perruchet & Pacton, 2006). For the sake of parsimony, this study will not differentiate between these terms and will use the term sequence learning¹.

Difficulties in sequence learning have been found to underlie various developmental and language disabilities, such as SLI. While relationships between sequence learning and language impairments seems robust in group-level analyses based on extreme-group designs (e.g. comparing kids with SLI to their typically developing peers), in order to truly untangle the relationship between sequence learning and language development, one needs to look at direct relationships by examining the role of individual differences in sequence learning in relation to various and specific aspects of language development. Research on sequence learning and language abilities has typically used group-level analyses, this has been informative and has answered a range of research questions, (such as whether children with SLI show deficits in sequence learning compared to typically developing children). However, many research questions arise that group-level research design cannot answer (e.g. is vocabulary size related to sequence learning?). Furthermore, extreme-group designs can also be problematic for multiple reasons. For example, even though extreme-group designs increase the ability to detect effects between groups, the nature of these designs also increases the probability of making a Type I error due to inflated effect sizes (Conway et al., 2005; Preacher et al., 2005; Unsworth, Redick, McMillan, Hambrick, Kane, & Engle, 2015). Furthermore, treating groups of children with language impairments and developmental delays as homogenous is not always an ideal approach as children with language impairments typically range in terms of abilities and difficulties. Thus,
using individual differences research, one can tackle the limitations associated with using an extreme-group approach. In this study we adopt an individual differences approach to assess relationships between sequence learning and motor coordination in relation to specific aspects of language abilities. A research question that group-level analyses, while important, cannot address.

**Measuring sequence learning.** Before moving on to discuss the literature on language development and sequence learning, it is important to mention that multiple tasks have been used in the literature to examine sequence learning. Such tasks are typically experimental in nature and designed so that the order of stimuli is based on a set of rules that is complex enough that the participant is unable to describe the underlying rules or patterns. The Serial Reaction Time (SRT; Nissen and Bullemer, 1987) is one of the most commonly used visual sequence learning task. We will only describe the SRT task in this section as it is the one we adopt in this study (for a description of other tasks used to examine sequence learning in the literature, refer to Obeid, Brooks, Powers, Gillespie-Lynch, & Lum, 2016).

In a typical SRT task sequences of visual stimuli appear at one of four positions on a computer screen. Each position corresponds to a button on a stimulus pad; as each stimulus appears, the participant is required to press the corresponding button as quickly as possible. In this task the stimuli may follow either: (1) a fixed sequence that, through sequence learning, leads participants to anticipate the location of each successive stimulus in the series or a (2) random sequence where the location of the stimuli is not based on a predetermined order. Learning is measured through reductions in reaction times for blocks of trials following the fixed sequence, as compared to blocks of trials following the random sequence (Nissen & Bullemer, 1987; Robertson, 2007). The SRT task has been prominently used in group-level research to
examine the Procedural Deficit Hypothesis among a range of developmental disabilities (see meta-analyses: SLI: Lum et al., 2014; Dyslexia: Lum et al., 2013; Autism: Foti et al. 2015, SLI & Autism: Obeid et al., 2016).

**Phonological Ability and Language Acquisition**

As previously mentioned, the procedural deficit hypothesis suggests that language impairments are due to a deficit in procedural memory. The procedural deficit hypothesis links phonology to procedural memory, but restricts vocabulary to the declarative memory system. This is not quite in line with the literature supporting robust associations between children's phonological skills, their vocabulary size, and word learning abilities (Coady & Evans, 2008; Gathercole & Baddley, 1990a; 1990b). Children's learning of novel words is critical for their language acquisition. Research has shown that the ability to repeat novel phonological words plays an important role in children's language development, particularly their vocabulary development (Gathercole & Baddley, 1990a; 1990b). Each word that we now commonly use was at one point a phonologically vague and novel word that we had to be able to repeat in order to learn it (Gathercole, 2006). Children attempt to repeat novel sounding words all the time as they are learning new words, and their ability to do so successfully has been linked to their learning of these novel words. This relationship is bidirectional in nature (Coady & Evans, 2008), as children's vocabulary size also plays a role in their ability to successfully repeat newly sounding words. This ability to repeat novel words involves both the ability to hold the words in one's short-term memory long enough to reproduce them and the ability to accurately pronounce these new sounds, and thus may be termed phonological short-term memory (Coady & Evans, 2008). Children's phonological short-term memory is typically assessed using the nonword repetition task, which has been regarded as a clinical marker for specific language impairment (Archibald
Gathercole, 2007; Botting & Conti-Ramsden, 2001). This task has been typically called a measure of phonology or phonological short-term memory. For parsimonious reasons, we will refer to nonword repetition as a measure of phonology, as opposed to phonological short-term memory, throughout this dissertation.

The relationship between vocabulary acquisition and the ability to repeat nonwords successfully has been shown to be bidirectional, children who have larger vocabularies are better at repeating complex nonwords, furthermore, children who have good phonological skills are quicker to learn new words (Gathercole & Baddley, 1990a; Baddeley, Gathercole, & Papagno, 1998). We already know a lot about the role of nonword repetition in relation to children's language development. In fact, research has robustly shown that children with language impairments show difficulties on tasks of nonword repetition. One prominent theory suggests that delays in language development may be due to a possible underlying impairment in children's abilities to repeat back phonologically novel words, or nonwords (such as: “kesenun”, Archibald & Gathercole, 2007). Since phonology is related to the ordering of the sounds in language and thus associated with procedural and sequence learning (Ullman, 2004) but also with vocabulary acquisition (Gathercole & Baddley, 1990a), we were interested in examining this measure of nonword repetition as a bridge between the words versus rules dichotomy. This dichotomy was originally suggested by dual-route theorists of language acquisition, however, there is a possibility that nonword repetition is associated with procedural and sequence learning, but also rule-based aspects of language (i.e., vocabulary). The idea that nonword repetition is association with vocabulary learning has been supported by multiple studies in the field, however, to our knowledge no research has attempted to examine the role of nonword repetition with the procedural/declarative model. In this study, we attempt to examine whether phonology
is, in fact, related to procedural memory by examining the relationship between sequence learning and children's phonological abilities, tested using a nonword repetition task.
CHAPTER 2
Sequence Learning and Language Development

Sequence Learning in Relation to Individual Differences in Grammar

Studies focusing on individual differences in sequence learning in relation to language abilities remain relatively scarce. This may be due to some research finding that individual differences in sequence learning remain robust across populations that vary in age and intelligence (e.g., Reber, 1993; Stanovich et al., 2009). However, recently there has been a resurgence of interest in individual differences in sequence learning and various other cognitive and linguistic abilities (e.g., Kidd, 2012). The literature on the relationships between sequence learning and language remains rather contradictory (see Kidd & Kirjavainen, 2011; Lum & Kidd 2012). While our interest for this dissertation lies in child language development, due to the paucity of research focusing on children and the conflicting findings in the field, this section will discuss the available literature on the role of sequence learning in grammatical ability in both child and adult populations. In line with the dual-route approaches to language development, we would expect the literature to find supporting relationships between grammatical ability and sequence learning.

Child literature examining sequence learning and grammatical ability. After Ullman and Pierpont’s (2005) influential paper on the procedural deficit hypothesis most of the studies assessing grammatical abilities and sequence learning have tried to evaluate this proposed deficit in procedural learning. In what may be the first study to examine sequence learning in children with SLI and age-matched controls, Tomblin, Mainela-Arnold, and Zhang (2007) found support for the procedural deficit hypothesis. Using the SRT task as a measure of sequence learning, the
authors found that adolescents with SLI showed difficulties in learning the sequences compared to age-matched controls. The authors then found that similar learning difficulties were evident when the groups were divided based on grammatical ability, but not when language impairments were defined based on vocabulary scores. While this was not an individual differences study, relationships between sequence learning and grammatical ability (but not vocabulary abilities) were linked to performance on the SRT task — in line with the PDH. Similarly, by adopting an individual differences approach with a sample of 100 children between the ages of 4 to 6, Kidd (2012) found that children who displayed greater sequence learning (measured using the SRT task) were more likely to produce complex passive sentences (e.g. the door was opened by the boy) after being primed by an experimenter using the passive-tense to describe previous scenes. The studies described above offer support for a possible relationship between sequence learning and aspects of children grammatical abilities (e.g., producing complex passive sentences when primed).

However, the relationship between sequence learning and grammatical abilities is not as clear-cut as it may initially seem. Two other studies by Kidd (Kidd & Kirjavainen, 2011; Lum & Kidd 2012) have failed to find a relationship between performance on the SRT task and children’s production of past-tense morphology. In their first study, Kidd and Kirjavainen (2011) examined the declarative/procedural model set forth by Ullman and Pierpont (2005) with 124 Finnish children between the ages to 4 to 6. The authors used the SRT task, in addition to tasks of declarative memory, past tense knowledge, vocabulary, and nonverbal intelligence. In support of the PDH, the authors found a relationship between tasks of declarative memory and vocabulary. However, performance on the SRT task was not related to performance on the task of past-tense production, which was correlated with declarative memory but not procedural
memory. Similarly, in a study of 58 typically developing 5-year-olds, Lum and Kidd (2012) examined whether the procedural and declarative memory systems were related to children’s past-tense use and vocabulary knowledge. Results showed that children’s use of regular and irregular past-tenses was unrelated to any of the memory systems, undermining the link between grammar and procedural memory in the PDH. However, the authors did find evidence supporting the other half of the PDH, linking vocabulary to performance on the declarative memory task, which was in line with findings by Kidd & Kirjavainen (2011). In a study of 5 to 10-year-old children with hearing impairment, Conway et al. (2011) assessed sequence learning using a novel visual version of the Artificial Grammar Learning (AGL) task. The traditional AGL task (Miller, 1958; Reber, 1967) typically presents participants with auditory or visual sequences of stimuli (such as nonsense syllables or letters) that are generated based on a complex set of rules. After a period of exposure to those sequences, participants are tested on their sequence learning by taking part in a forced choice task where they are required to differentiate between familiar and unfamiliar sequences. Conway et al. (2011) found relationships between individual differences in sequence learning and standardized assessments of sentence processing (i.e., formulating and recalling sentences subtests of the Clinical Evaluations of Language Fundamentals–4), after controlling for vocabulary size, verbal working memory, and duration of cochlear implant use.

The mentioned studies show mixed support for the PDH: sequence learning (measured using the SRT task) does not seem to be associated with all aspects of grammar. In fact, the relationship that Tomblin et al. (2008) noted was a result of looking at groups divided based on grammar scores as opposed to direct associations. We currently have little support for linking individual differences in grammatical abilities to children’s performance on the SRT task in
particular. Only one study by Kidd (2012) which adopted the SRT task was able to report links between individual differences on sequence learning and children's sentence processing abilities and their production of complex passive sentences. Furthermore, the adult literature seems to show a different pattern. While it is possible that adult-like processes which support language learning are very different from the processes which support child language acquisition, there is enough of a scarcity of evidence that is worth considering the findings coming from adult research to piece together what may underlie some of the contradictory findings surrounding the PDH.

**Adult literature examining sequence learning and grammatical ability.** In a series of three studies with adults, researchers found that performance on a sequence learning task was related to performance on a task of word predictability (Conway, Bauernschmidt, Huang, and Pisoni, 2010). To examine sequence learning, the researchers used a novel visual version of the Artificial Grammar Learning task aimed at examining the relationship between sequence learning and sentence processing. The sentence processing task required participants to predict the last word in a sentence based on sentences they have previously heard during a familiarization phase. Half of the sentences during the prediction/testing phase had a final word that was predictable based on the context of the sentence (e.g. *He rode off in a cloud of dust*) the other half had a final word with no predictability (e.g. *The first man heard a feast*). Performance on the sequence learning task was related to performance on the task of word predictability. Using two different measures of artificial grammar learning, Misyak and Christiansen (2007) also found a relationship between measures of sequence learning and language processing among adults. It is noteworthy, however, that there was no significant correlation between the separate
Artificial Grammar Learning tasks suggesting that these tasks may be measuring different underlying abilities.

In several studies, Misyak and colleagues (Misyak, Christensen & Tomblin; 2010a, 2010b; Misyak & Christiansen, 2012) used a novel task of sequence learning which combined both the AGL and SRT tasks into one online learning paradigm. In this task, participants were provided with auditory-visual strings of nonwords based on an artificial grammar. Strings consisted of a complex grammar based on the rules of: $aXd$, $bXe$, and $cXf$, where $a — f$ represent nonwords. Ungrammatical strings did not comply with the grammatical laws of this artificial language. After the familiarization phase, participants were seated in front of a computer screen where they heard series of nonwords and were required to click on different parts of the written nonword as soon as it was heard. Results showed that this novel task of sequence learning was correlated with participants’ accuracy in comprehending complex sentences (e.g., *The evidence that was examined by the lawyer turned out to be unreliable*). These findings remained significant even after controlling for verbal working memory and nonverbal intelligence. These results from the adult literature seem to offer support for the role of sequence learning in spoken word production in adults, however, the generalizability of such results to children is risky as adult language learners tend to rely on different processes from those used by children in language development.

Research on adult second language learning has found significant associations between sequence learning and tasks of grammatical processing. For instance, Frost, Siegelman, Narkiss, and Afek (2013) used a visual version of the commonly used speech stream task. In a typical speech stream task, participants briefly listen to a speech stream comprising three-syllable nonsense words integrated into a random sequence, with each nonsense word occurring multiple
times. Participants are then tested using a forced choice task on their ability to distinguish the recurring three-syllable nonsense words from other novel three-syllable sequences (Saffran et al., 1996). Using a visual-version of this task, Frost et al. (2013) found relationships between performance on the sequencing task and adult's acquisition of the morphological structure of Hebrew words among 27 college students. These findings remained significant even after controlling for nonverbal intelligence and verbal working memory. Kaufman et al. (2010) noted significant relationships between performance on the Alternating Serial Reaction Time task — which is similar to the SRT tasks except that random items are inserted within the sequence of trials to minimize explicit knowledge — and performance on proficiency exams of foreign language learning (French or German) among 153 adolescents. These findings were significant even after controlling for working memory, nonverbal intelligence, and processing speed. In a study that also employed the ASRT task, Granena (2013) found relationships between performance on tasks of sequence learning and individual differences in sensitivity to grammatical-agreement rules in adult bilinguals who learned Spanish after the age of 16. Using the same visual version of the AGL task that was used Misyak and Christiansen (2007), Brooks and Kempe (2013) found a relationship between individual differences in an adult Russian learning task and accuracy on the AGL task. While performance on the AGL task was associated with the learning of Russian case-markings, it was not related to vocabulary acquisition or grammatical generalizations to new words.

Research examining the relationship between sequence learning and grammatical abilities remains inconclusive at best. There has been a handful of studies among children and adults looking at individual differences in sequence learning and different areas of grammar abilities. Some of these studies offer support for the procedural deficit hypothesis (e.g., Kidd, 2012),
however, others do not (e.g. Lum & Kidd, 2012). Such inconsistent findings may be due to the use of a wide range of measures of sequence learning that might not be measuring the same underlying concept (Siegelman et al., 2016). Further research is needed to examine direct relationships between children's grammatical abilities and individual differences on tasks of sequence learning in order to pinpoint what relationship may exist between these two variables. In this study we assess direct relationships between individual differences in sequence learning in relation to children’s grammatical abilities.

Sequence Learning in Relation to Vocabulary Development

In line with the procedural deficit hypothesis, we discussed research linking performance on tasks of sequence learning to rule-based aspects of language learning. The question remains as to whether vocabulary development is related to sequence learning. While the PDH suggests that vocabulary learning is unrelated to sequence learning, infancy researchers focusing on word segmentation postulate that sequence learning is in fact very much related to children's word learning and their ability to map words onto their referents in the environment (Erickson & Thiessen, 2015).

Infancy researchers have mostly examined sequence learning using the Speech Stream task. This task was first developed by Saffran and her colleagues (1996) who were able to show that infants can extract word forms from continuous speech by picking up the sequencing rules of syllable occurrences from the environment. The ability to segment words is a prerequisite for mapping these words onto their referents and hence learning the meanings of the words. In a sample of 17-month infants, Estes, Evans, Alibali and Saffran (2007b) demonstrated a relationship between performance on the speech stream task and linking words to objects, as
measured using an object labeling task. In another study with SLI and typically developing children, Evans, Saffran, and Robe-Torres (2009) noted that in typically developing children, performance on the speech-stream task was correlated with scores on receptive and expressive vocabulary. As opposed to the literature in the previous section linking sequence learning solely to rule-based aspects of learning, Evans et al. (2009) found that performance on the speech-stream task was only correlated with receptive vocabulary scores among children with SLI. Similarly, Shafto, Conway, Field and Houston (2012) showed that infants’ performance on a visual sequencing task was associated with their vocabulary comprehension at the time of testing and vocabulary development 5 months later.

In the adult literature, Mirman, Magnuson, Estes, & Dixon (2008) found relationships between sequence segmentation and word learning in adults. Speciale, Ellis, and Bywater (2004) found a relationship between phonological sequence learning and vocabulary acquisition in second language learning in adults. However, no relationship was reported between sequence learning and vocabulary ability of first language. Conversely, Misyak and Christiansen (2007) found no relationships between vocabulary abilities and performance on a task of sequence learning among college students.

Several of the studies mentioned in this section reported relationships between vocabulary scores and performance on sequence learning tasks. While the child literature remains scarce, significant associations between sequence learning and vocabulary abilities are not in support of the PDH which suggests that we learn words declaratively. It is noteworthy that the tasks described in this section are not the same as those measured in the preceding section, for instance none of the studies described in this section used the SRT task. The studies that did use the SRT task did not report relationships between performance on the task and vocabulary
scores (Kidd & Kirjavainen, 2011). Thus, we can conclude that results are inconclusive at best, with some studies reporting relationships between sequence learning and vocabulary and other studies offering no such support. More research is needed to untangle the relationship between sequence learning and lexical development. Existing research suggests that Ullman’s PDH should recognize contributions of sequence learning and its role in vocabulary development. However, a possible revision of the PDH hypothesis might be necessary as the current findings linking sequence learning to word learning may generally challenge the dual mechanism paradigm for language processing. The question remains as to whether we learn different aspects of language (grammar and phonology versus vocabulary) based on different principles of learning and memory (see Pinker, 1994; Bates & Goodman, 1997). More research is needed to examine what aspects of vocabulary development may be associated with sequence learning. Thus in this study we will examine whether a relationship exists between sequence learning and individual differences in children’s vocabulary abilities in our attempt to try to understand the role of sequence learning in relation to different aspects of language.

**Sequence Learning and Nonword Repetition as a Measure of Phonology**

In line with the procedural deficit hypothesis, phonology is typically associated with sequence learning and children with language impairments generally show difficulties in phonological aspects of language learning. Thus, while the PDH suggests that phonological skills are associated with sequence learning, the literature has also linked performance on tasks requiring the repetition of phonologically novel words to children's vocabulary acquisition (Gathercole, 2006; Gathercole & Baddley, 1990a). Performance on tasks of nonword repetition have been found to be good measures of language delay and a clinical marker for SLI (e.g., Bishop, North, & Donlan, 1996; Gathercole & Baddley, 1990a). Furthermore, because the PDH
attempts to pinpoint the underlying deficits of SLI, it is critical for researchers and clinicians alike to pinpoint the exact relationships between measures of sequence learning and nonword repetition. Since the nonword repetition task is considered a clinical marker of SLI and the PDH suggests that sequence learning is an underlying deficit in language impairment, examining the role of nonword repetition in relation to sequence learning seems to be critical for us to be able to find associations between children’s sequence learning abilities and how that is associated with their nonword repetition skills.

In studies with clinical groups, Gathercole and Baddley (1990b) compared the phonological skills of a group of language impaired children to typically developing controls matched on both verbal and nonverbal intelligence. The language impaired group showed significant difficulties repeating nonwords compared to both peers matched on verbal ability and those matched on nonverbal intelligence. These findings suggest that nonword repetition not only plays an important role in children's language abilities, but is also good at discriminating language disordered children. It is noteworthy that the nonword repetition task is not a pure measure of phonology but involves a memory/attention aspect since it requires participants to retain the nonwords in their short-term memory before being able to repeat them. To examine whether difficulties in nonword repetition are particularly related to difficulties in short-term memory in general, Archibald and Gathercole (2007) examined the performance of 16 children with SLI on the nonword repetition task and a task of serial recall, as a general measure of short-term memory. Results showed that compared to their typically developing peers, children with SLI performed worse on both tasks of short-term memory, however, there was a larger difference between SLI and control groups in performance on the nonword task, suggesting a disproportional impairment in performance on nonword repetition compared to a typical task of
short-term memory. The authors conclude that nonword repetition is not only a measure of short-term memory, rather this task is a unique measure of both short-term memory and phonological ability since it taps into individual's abilities at repeating a series of unfamiliar phonological sequences and hence is an important and unique marker for language impairment. Similarly, Henry, Messer, and Nash (2012a) showed that compared to typically developing children, children with SLI and children with language difficulties reported weaker nonword repetition (measured using the nonword repetition task). These findings remained robust in the SLI children even after controlling for age, verbal, and nonverbal IQ, which suggests that such difficulties may go beyond verbal deficits that are typically reported in language impaired individuals. These findings of a disadvantage at successfully repeating nonwords among language impaired children was confirmed in a meta-analysis of 23 studies examining performance on the nonword repetition task among children with SLI where Estes, Evans, & Else-Quest (2007a) found that children with SLI showed large impairments in nonword repetition even when repeating short nonwords.

There has also been research examining nonword repetition in typically developing children. In a study examining causal links between accuracy on the nonword repetition and children's abilities to learn novel words, Gathercole & Baddley (1990a) recruited children between the ages of 5 and 6 and had them learn both familiar and unfamiliar names for toy animals in addition to taking part in a nonword repetition task. Children were then divided into groups based on their performance on the nonword repetition task. Children who struggled with nonword repetition also struggled with learning the new unfamiliar toy animal names thus suggesting that a close relationship exists between word learning and nonword repetition. Similarly, Service (1992) found that Finnish children between 9 and 10 years of age who were
better at nonword repetition were also better at learning English words. Similarly, Michas and Henry (1994) found that 5-year-old children who were better at nonword repetition were also better at learning novel words from a foreign language.

Individual differences research has highlighted the bidirectional relationship between vocabulary development and phonological abilities, measured using the nonword repetition task (for a review of research using the nonword repetition task among typical and language impaired children see Coady & Evans, 2008). For instance, longitudinal research has shown relationships between vocabulary growth and nonword repetition in early childhood (Gathercole, Willis, Emslie, & Baddley, 1992). In addition to research showing relationships between nonword repetition and novel word learning (Gathercole, Hitch, Service & Martin, 1997) and reading proficiency (Nation & Hulme, 2011). Furthermore, robust and consistent findings have reported that language impaired individuals show deficits in nonword repetition. While the PDH proposes a connection between two long-term memory systems and different components of language ability, no research has yet examined the role of individual differences in short-term memory, specifically phonological short-term memory, and its relationship to sequence learning even though research has noted difficulties in nonword repetition in children with language impairments (see Coady & Evans, 2008; Estes, Evans, & Else-Quest, 2007a). If an impairment in procedural learning underlies language impairment and phonology is thought to be associated with rule-based aspects of language, then we would expect a relationship to exist between sequence learning and performance on a nonword repetition task. If such a relationship exists, it will allow us to further understand the nature of sequence learning in relation to various aspects of language abilities.
CHAPTER 3
Motor Skills, Cognitive Abilities, and Language Development

Theorists and researchers have long been interested in whether language abilities develop in isolation, or whether children's development of their language abilities is also associated with other areas of development, such as motor development (see Bates & Dick, 2002). Language acquisition is a highly complex, high-order process with multiple variables contributing to its development, thus examining the roles of memory and cognitive systems of learning are not the only steps in the pursuit of uncovering the nature of language development. The interest in looking at the relationship between language and motor development in children grew out of the work of prominent theories such as Piaget's domain-general view regarding the shared development of verbal and nonverbal abilities in the stage of sensorimotor development (Bates & Dick, 2003; Bates & Snyder, 1987; Beard, 2006; Karmiloff-Smith, 1995; Piaget, 1999). Like Piaget, Dewey and Vygotsky also stress the importance of both the sensory and motor functions in development as crucial components of early childhood (Stetsenko, 2016). Emerging from the domain-general approach to development is the notion of embodiment, which suggests that the body plays an important role in development and in turn, cognition is a product of perceptual and motor capabilities that drive one's experiences (Thelen & Bates, 2003; Iverson & Thelen, 1999) as opposed to viewing the body as an output device merely executing the commands of the mind. As Stetsenko (2016, p. 295) puts it "The mind is stretched or distributed across the body and the external resources drawn upon to support its workings". Similarly, Iverson and Thelen (1999) argue that both speech and gesture (i.e. the hand and the mouth) are tightly linked to one another and critical for the development of language as a cognitive activity. The authors provide support for their theories through neuropsychological research showing that in adults, language and
movement are very closely related in the brain. The authors then move on to discuss why this might be the case and argue that the development of motor actions of the hand and the mouth are present from birth and co-develop during the first year of life. In line with Iverson and Thelen's (1999) approach, Bates and Dick (2002) argue for the unification of gesture and language, they offer evidence that children develop linguistic and gestural abilities at around the same time, and argue that these two aspects of development are also linked in the brain, suggesting that the two abilities are not neatly divided in the brain. Similarly, in "Beyond Nature-Nurture: Essays in Honor of Elizabeth Bates", Volterra and colleagues (2005) present research supporting the views that children's vocal and linguistic abilities develop at around the same period of time and correlate in relation to frequency of use and rates of acquisition. In a review article, Diamond (2000) suggested that motor and cognitive development are “fundamentally intertwined” with the cerebellum playing a large role in both motor and cognitive functioning. Similarly, Iverson (2010) argues that the development of motor skills in infancy sets the stage for the development of skills needed for language acquisition, similar to the description of sensorimotor development by Piaget. Iverson (2010) also sheds light on research showing that children with language impairments show difficulties in various aspects of motor functioning, such as fine motor coordination.

While the majority of the current literature regards language development and motor coordination as separate sub-disciplines of developmental science, the question remains as to how these two aspects of development are related (Diamond, 2000). If language functions as predicted the PDH, rule-based aspects of language learning and motor abilities should both be related to procedural memory. However, if a more domain-general structure is closer to the real model of cognitive and linguistic functioning, then we would expect that all aspects of language
to be associated with one another, but also with motor skill, which is in line with single-route approaches to language development (Bates & Dick, 2002; Bates & Goodman, 1997; Bates et al., 1992; 1995; Volterra, Caselli, Capirci, & Pizzuto, 2005). Research is needed to be able to look at direct associations between specific aspects of motor abilities, such as fine motor coordination, and language abilities. In line with the view that language and motor abilities are in fact linked, some researchers have postulated that communication and motor delays in children are a result of a common underlying neurodevelopmental impairment (Wang, Lekhal, Aaro, & Schjolberg, 2012). This is also important in light of the PDH because of how procedural memory is so tightly linked with motor coordination.

In line with research linking motor and language development, there has been a plethora of literature showing that children with developmental disorders, including Attention Deficit Hyperactive Disorder (ADHD), dyslexia, language disorders, and Autism Spectrum Disorder show difficulties in both language abilities and motor coordination (Bedford, Pickles, & Lord, 2015; Leonard, Bedford, Pickles, Hill & BASIS Team, 2015; Leonard & Hill 2014; Diamond, 2000). Such relationships between motor skills and language development have been supported in clinical studies (see Leonard & Hill 2014 for a review). While research has shown that children with language impairments and developmental disabilities show deficits in motor skills, research examining individual differences in language abilities and motor skills of typically-developing school-aged children remains limited. This literature, while limited, seems to offer support for the PDH by attempting to link rule-based aspects to language to children's motor abilities (see DiDonato Brumbach & Goffman, 2014). However, there does not seem to be research examining the PDH in light of a co-occurring motor coordination and sequence learning difficulty. The question remains as to what specific aspects of these language abilities (e.g.,
vocabulary, grammar, phonology) are related to motor skills. Here again we attempt to divert from group-level differences and focus on individual differences in order to find direct associations between specific measures of language abilities (vocabulary, grammar, and phonology) in relation to motor coordination. Before moving on to the individual difference research targeting motor coordination and language, we will discuss clinical studies which have evaluated difficulties in both motor and language skills before moving on to literature that is in line with our research goals: understanding the relationship between motor coordination and language abilities in a community sample of school-aged children.

Research with Clinical Populations

There is support in the literature suggesting a relationship exists between language difficulties and motor impairments. The majority of this literature focuses on group-level differences by looking at groups of children with language difficulties in relation to their typically developing peers. In a sample of 23 school aged children with dyslexia and 23 typically developing children, Leslie, Davidson, & Batey (1985) showed that children with dyslexia were slower at completing the Pegboard task (a commonly used measure of fine motor coordination and manual dexterity, Roebers & Kauer, 2009) compared to typically developing peers, suggesting that a language disorder typically co-occurs with motor impairments. This co-occurrence may indicate that an underlying system (i.e. the procedural system) which, when it does not operate typically, may result in atypical development in the functioning of both of these developmental areas. Similarly, Owen and McKinlay (1997) found that children between the ages of 4 to 7 with speech and language disorders were slower on motor tasks compared to their typically developing peers (N = 16). The authors recommended that children with language impairments need to be assessed for motor difficulties as well in order to ensure that appropriate
interventions are available. Zelaznik & Goffman (2010) also showed that children with SLI (N = 14) between the ages of 6 and 8 performed poorly on tasks of fine and gross motor skills compared to typically developing controls. In support of the view that children with SLI show difficulties beyond linguistic abilities, Adi-Japha, Strulovich-Schwartz & Julius (2011) showed that 5-year-old children with language impairments (N = 16) were slower than age-matched controls on tasks of visual and motor integration. After training, the kids with SLI seemed to be as fast as their peers on the tasks, however, error analyses showed that there was a speed for accuracy trade of even after training in the language impaired group.

DiDonato Brumbach & Goffman (2014) examined the relationship between language production, speech-motor, and fine motor skills in children with SLI. Participants included 11 children with SLI and 12 typically developing age-matched controls (4 to 6-year-olds). The authors found that children with SLI showed delays in speech-motor and fine motor skills. The authors then examined direct correlations between measures of gross and fine motor skills in relation to cognitive and language measures. Results showed that compared to their peers, children with SLI showed co-occurring difficulties in tasks of phonology and fine motor skill. The authors did not find relationships between fine and motor skill in relation to cognitive and linguistic measures when examining relationships in the sample as a whole. It is noteworthy that DiDonato Brumbach & Goffman (2014) did not look at specific measures of vocabulary, grammar, or reading in relation to motor skill, the authors also used the nonword repetition task to characterize their sample but did not mention whether this task was directly correlated with motor skill at all. The authors conclude that the PDH offers insights into their findings by linking motor and language development. In a sample of children with intellectual and developmental disabilities, Houwen, Visser, van der Putten, & Vlaskamp (2016) found strong correlations
between motor, cognitive, and language domains. They concluded that cognitive and language abilities in children with developmental disabilities are related to both fine and gross motor skills and hypothesized that early motor and cognitive interventions may play a role in enhancing language abilities. Conversely, Estil, Whiting, Sigmundsson, & Ingvaldsen (2003) suggested that not all children with language impairments show deficits in motor abilities. They concluded that when motor and language impairments do co-occur, children typically experience difficulties in fine motor skills in particular.

Fine motor coordination is integral to children's daily activities, from completing schoolwork to painting and drawing. In this study, we focus on fine motor coordination because clinical research seems to find strong associations linking language delays to difficulties in areas of fine motor control (e.g., Zelaznik & Goffman, 2010). When examining these findings in light of the PDH framework, this relationship is not that surprising considering motor abilities and sequence learning are both associated with procedural memory. We already know from group-level research that children with SLI and dyslexia show difficulties in sequence learning (Lum et al., 2014; Lum et al., 2015), thus children's co-occurring language and motor difficulties seem to be aligned with the PDH. However, while the group-level research seems to be rather robust, a lot of questions regarding the nature of sequence learning and motor coordination in relation to specific language measures remain unanswered (such as: what aspects of language abilities would be related to sequence learning and/or motor coordination?).

**Individual Differences Literature**

**Language skills.** The clinical research seems to consistently report relationships between language delay and difficulties in fine motor skill (e.g., Zelaznik & Goffman, 2010). In order to understand the direct relationships between language and motor functioning, we will discuss the
literature in light of individual difference research. Despite the importance of motor skills in children's daily lives, especially the school setting (e.g. writing, drawing, tracing), very little research has examined direct relationships between fine motor skill in relation to language abilities and academic achievement in school-aged children. Instead, most of the literature has focused on comparing the fine motor of children with and without language and developmental delays (Adi-Japha et al., 2010; DiDonato Brumbach & Goffman, 2014; Zelaznik & Goffman, 2010).

The individual differences research on language and motor skill remains scant. For instance, Oudgenoeg-Paz, Volman, & Leseman (2012) showed a relationship between vocabulary development and walking ability in infants between the ages of 16 to 28 months. In a large cohort study, Wang et al. (2012) had mothers complete questionnaires about their children’s motor and communicative abilities at ages one and a half and again at 3 years of age. Maternal reports showed that communication and motor abilities were significantly correlated with one another when the children were 1;6 years of age. Furthermore, motor abilities at the younger age predicted communication abilities at age 3. The authors concluded that communication and motor difficulties are not separate abilities and may in fact be manifestations of a common and underlying neurodevelopmental delay. More recently, King-Dowling, Missiuna, Rodriguez, Greenway, & Cairney (2015) showed that deficits in motor coordination were associated with lower language scores in preschool children (N = 214) between the ages of 3 to 6 years.

The literature, while limited, seems to offer a link between motor abilities and children's linguistic skills. These relationships seem to be in line with the PDH, suggesting that motor skills and rule-based aspects of language (grammar, phonology) are related to one another. This
prompts us to examine the role of children’s motor skills in relation to aspects of sequence learning, but also makes one wonder about the relationship between motor skills in relation to particular aspects of language (words vs. rules).

**Phonology.** While research has not examined the role of fine motor skill in relation to phonological abilities, there has been considerable research linking performance on nonword repetition to speech motor performance in both children and adults. For instance, research from populations with speech motor difficulties supports the importance for looking at speech motor processes in relation to nonword repetition. Research has shown that children who stutter show difficulties in repeating nonwords compared to typical controls (Anderson, Wagovich, Hall, 2006; Hakim & Ratner, 2004) suggesting that children who stutter may have an underlying phonological short-term memory impairment. Research has also confirmed that associations exist between speech motor abilities and performance on tasks of nonword repetition. Furthermore, improvements in speech motor coordination were noted after having to repeat complex nonwords among both children and adults (Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010).

While we hypothesize that performance on a task of nonword repetition will be associated with measures of fine motor coordination, to our knowledge there is really no literature looking at relationships between fine motor coordination and aspects of nonword repetition. Thus, this aspect of our study remains an exploratory one, if our hypothesis – which suggests links between nonword repetition and motor skill – is supported, it would offer interesting insights about the relationship between motor coordination and verbal-cognitive processing in young children, a relationship that may frequently be overlooked.
Cognitive Functioning. The literature has not only looked at associations between motor skills and language abilities, but there has also been interest in examining the role of motor coordination and various aspects of cognitive abilities. Research has found support for relationships between motor coordination and various measures of cognitive functioning. For instance, Wassenberg et al. (2005) reported positive correlations between motor performance, visual motor integration, working memory (girls), and verbal fluency (boys) in 378 five to six-year-old children. Roebers & Kauer (2009) set forth to examine correlations between measures of motor coordination and cognitive abilities in 112 seven-year-old children. While some overlap existed between cognitive and motor tasks, these associations were weak. The authors concluded that some overlapping properties may be involved in mastering motor and cognitive tasks. Davis, Pitchford, & Limback (2011) reported significant relationships between overall cognitive abilities and motor skills in 248 four to eleven year olds. Similarly, Roebers et al. (2014) found relationships between fine motor skill, non-verbal intelligence, and executive functioning in 5 to 6-year-old children. Conversely, Jenni, Chaouch, Caflisch, & Rousson (2013) found that while motor development may be related to intelligence in typically developing children, the correlations were weak, suggesting that these areas of development tend to occur independently. These findings, while mixed, seem to suggest that while motor coordination and cognitive skills are generally regarded as two distinct aspects of development, they tend to be associated with one another. Due to literature linking motor skills to aspects of cognitive functioning, and because language impairment has been associated with difficulties in verbal working memory (Leonard et al., 2007), this study controls for working memory in all analyses by incorporating a nonverbal measure of working memory.
CHAPTER 4

Research Goals and Rationale

To further understand the relationships between motor abilities, sequence learning, and language impairment, one needs to examine direct associations between individual differences in various aspects of language development, motor abilities, and cognitive processing. The child literature on relationships between sequence learning, motor skills, and individual differences in language development remains scarce and controversial, hence the pressing need for more research linking variations in individuals’ abilities to variations in language abilities. Understanding these relationships can have broader implications on developing interventions targeting sequence learning and fine motor skill in children with delays in certain aspects of language or cognitive abilities.

Most studies aimed at evaluating the procedural deficit hypothesis have relied on extreme-groups design (e.g., Tomblin et al., 2007). These studies have compared performance on tasks of sequence learning among language impaired populations (e.g. SLI, Dyslexia) and their typically developing peers (e.g. Lum et al., 2014). Such studies have consistently reported that individuals with specific language impairments do seem to show difficulties on tasks of sequence learning. While this is informative, the question remains as to what particular areas of language are associated with such difficulties on sequence learning. Being able to offer direct relationships between measures of language abilities and linking that to an underlying cognitive difficulty plays an important role in developing interventions targeted for different children with language impairments.

While group-level analyses answer important questions that researchers pose, individual differences research remains a much-needed approach in order to answer further questions. The literature on individual differences in sequence learning remains rather limited with some (but
not all) research showing relationships between sequence learning and rule-based aspects of learning (e.g., Misyak & Christiansen, 2007), and other research showing mixed findings in relation to associations between vocabulary and sequence learning (e.g., Estes et al., 2007b). In line with Pinker's (1998) dualistic-view of language acquisition, one would suspect that rule-based aspects of language development will be associated with measures of sequence learning (all centered in the procedural memory system), as opposed to word-level (i.e., vocabulary) aspects of language would not be related to sequence learning. However, if one was to look at the view of infancy researchers (e.g. Erickson & Thiessen, 2015), then sequence learning is imperative for children's abilities to associate a word with its object in the environment. Conversely, phonological short-term memory, while suspected to be procedural in nature, has been shown to be critical for children's vocabulary development (Gathercole et al., 1992).

Furthermore, in line with research theories emphasizing the relationship between motor and all aspects of language development in children (e.g., Bates & Dick, 2002; Iverson, 2010), researchers have emphasized the importance of studying the co-development of motor and language abilities suggesting that these two fundamental areas of child development are highly intertwined (see Diamond, 2002). In order to understand the relationships between motor development and language abilities, in this study we look at direct associations between children’s fine motor skills and their performance on a range of language assessments.

Furthermore, nonword repetition has been viewed as a critical clinical marker for the diagnosis of SLI and a measure for nonword repetition. According to the procedural/declarative model and the PDH, phonological skills in children are related to procedural memory and that is why children with SLI mostly show difficulties in syntax and phonology (Ullman & Pierpont, 2005; Ullman, 2004). In support of this view, research has shown that kids with SLI show
difficulties on tasks of nonword repetition (see Estes et al., 2007a for meta-analysis). However, prominent research has noted that nonword repetition is associated with children's abilities to learn new words (Gathercole, 2006; Gathercole et al., 1992) thus speaking to the idea that phonology might be an important aspect of procedural learning but also play a critical role in terms of word learning, and possibly supporting a single-route approach to phonological development in children. For this reason, we sought to uncover whether sequence learning was associated with performance on a task of nonword repetition. Additionally, because motor coordination plays an important role in procedural memory and learning, we also examined the associations between motor coordination and nonword repetition. To the best of our knowledge, no research has looked at fine motor skill in relation to nonword repetition, but research has shown associations between speech-motor ability and performance on the nonword repetition task (Sasisekaran et al., 2010). Finally, as a post-hoc and exploratory variable, we wanted to assess whether individual differences in sequence learning and motor coordination play a role in nonverbal intelligence, or whether the relationships are only restricted to verbal measures. Thus, we explored the relationship between sequence learning and motor coordination in relation to a commonly used measure of nonverbal intelligence. In line with Diamond (2000) we would expect to find relationships between motor coordination and cognitive assessments.

**Research Questions**

In this study, we used an individual differences approach to assess sequence and motor abilities in relation to language and cognitive skills in a community sample of 63 children between the ages of 6;0 and 10;8 years recruited from New York City and New Jersey. The data collected were used to address the following research questions.
• **Research Question 1. Sequence Learning and Language**
  Are individual differences in sequence learning related to language abilities? In particular, will there be a specific relationship between rule-based aspects of language (e.g., grammar, phonology) and sequence learning?

• **Research Question 2. Motor Coordination and Sequence Learning**
  In line with the procedural/declarative view of language and motor development. Will a relationship exist between measures of motor coordination and measures of sequence learning?

• **Research Question 3. Motor Coordination and Language**
  Are individual differences in fine motor skills related to language abilities? If so, what aspects of language abilities are particularly related to fine motor coordination (words versus rules)?

• **Research Question 4. Nonverbal Skills and Measures of Sequence Learning and Motor Coordination**
  Are individual differences in sequence learning and fine motor coordination related to non-verbal abilities?
CHAPTER 5

Method

Participants

Sixty-three children (33 girls; 30 boys) between the ages of 6;0 and 10;8 ($M = 8y; 2m$, $SD = 1;3$) took part in this study. Participants were recruited through a child subject pool and by posting flyers around the college and other institutions. All participants were from the New York City metropolitan area, primarily Staten Island and New Jersey. The sample was originally 66 children; however, one girl was removed because she was unable to pass any part of the nonverbal intelligence assessment and was unable to get through the trial section of the assessment. Two boys were dropped from all analyses because they were confirmed to have a diagnosis of Autism. Participants were 63.5% White, 12.7% Black/African-American, 6.3% Middle Eastern, 4.8% Latino/a, 1.6% Asian, 11.1% Mixed.

Participation took place over two sessions in a language study laboratory at the College of Staten Island. Families were compensated with a $20 Amazon gift card at the end of each session. Informed consent was obtained from parents. Children were asked for verbal assent. All parents were required to fill out an online background questionnaire about themselves and their children (see Appendix A). The majority of children in our sample were right-handed ($N = 58; 92.1\%$) with only 5 left-handed children (7.8\%). All participants were native speakers of English; ten children spoke another language in addition to English at home, which was verified using the background questionnaire (See Appendices B, and C for data extracted from the questionnaire).

Procedure

Testing occurred over 2 sessions, with each session lasting between 1 to 2 hours. Children completed a battery of language and cognitive assessments. All tasks were
counterbalanced across participants. Data for this study were drawn from a larger study examining individual differences in child language learning and temporal understanding. For brevity, this section will only describe the tasks and procedures that are relevant for the current study. Table 1 describes the tasks and measures and the sample's mean score and standard deviation on each of the tasks. The next section describes each of these mentioned tasks in detail.

All computerized tasks were administered on an Acer laptop using *E-Prime* 2.0 software (Schneider, Eschman, & Zuccolotto, 2002). All tasks that require recorded responses were coded using the *Sound Forge* software version 7.0.

Table 1

*Participants' Summary Data on All Tasks. Subtests are in italics, standard deviations in parentheses.*

<table>
<thead>
<tr>
<th>Type of Task</th>
<th>Tasks and Subtests</th>
<th>Raw Scores</th>
<th>Standardized Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal</td>
<td>Clinical Evaluation of Language Fundamentals - Fourth Edition (CELF–4)</td>
<td>—</td>
<td>105.3 (13.9)</td>
</tr>
<tr>
<td></td>
<td><em>Total Score</em></td>
<td>—</td>
<td>105.0 (14.6)</td>
</tr>
<tr>
<td></td>
<td><em>Receptive</em></td>
<td>—</td>
<td>106.5 (13.3)</td>
</tr>
<tr>
<td></td>
<td><em>Expressive</em></td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Verbal</td>
<td>Peabody Picture Vocabulary Test – Fourth Edition (PPVT –4)</td>
<td>146.4 (22.0)</td>
<td>112.7 (15.5)</td>
</tr>
<tr>
<td>Verbal</td>
<td>Test of the Reception of Grammar 2 (TROG)</td>
<td>14.9 (3.5)</td>
<td>102.4 (16.0)</td>
</tr>
<tr>
<td>Verbal</td>
<td>Nonword repetition task</td>
<td>70.8% (14.2%)</td>
<td>—</td>
</tr>
<tr>
<td>Nonverbal</td>
<td>Test of Nonverbal Intelligence – Fourth Edition (TONI–3)</td>
<td>20.8 (6.6)</td>
<td>113.8 (14.2)</td>
</tr>
<tr>
<td>Nonverbal</td>
<td>Pegboard task</td>
<td>94.2 (23.3) s</td>
<td>—</td>
</tr>
<tr>
<td>Nonverbal</td>
<td>Serial Reaction Time (SRT) task</td>
<td>92% (15%)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td><em>Simple Accuracy</em></td>
<td>37 (−7) ms</td>
<td>—</td>
</tr>
<tr>
<td>Nonverbal</td>
<td>Array Memory Task</td>
<td>64.5% (14.2)</td>
<td>—</td>
</tr>
</tbody>
</table>
Tasks and Measures

Assessments of verbal abilities. To assess the children's language abilities participants took part in several standardized language assessment measures including the Clinical Evaluation of Language Fundamentals–Fourth Edition (Semel, Wiig, & Secord, 2003), the Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007), and the Test for the Reception of Grammar – Second Edition (Trog-2; Bishop, 2003). Participants also took part in a verbal cognitive task: the nonword repetition task, as a measure of phonology.

Comprehensive Language Assessment. The Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF–4; Semel et al., 2003) is a standardized assessment typically used to evaluate an individual’s language abilities and assess whether a language disorder is present. This measure was used for the purpose of characterizing our sample. The CELF–4 a suitable assessment for individuals ranging from 5 to 21 years of age.

Participants completed the following subtests of the CELF–4: Concepts and Following Directions, Recalling Sentences, Formulated Sentences, Word Classes-Receptive, Word Classes-Total. Additionally, children aged 6 to 8 years completed the Word Structure and Sentence Structure sections; while children aged 9 to 11 years completed the Word Classes-Expressive section. These subtest yielded three scores that reflected participants’ (1) receptive, (2) expressive, and (3) total language abilities (see Table 1). This assessment took between 30–45 minutes to administer.

Grammar. The Test for the Reception of Grammar – Second Edition (TROG–2; Bishop, 2003) measures the understanding of grammatical contrasts starting from age 4 onto adulthood. The test targets sentence comprehension and contains 80 stimulus items arranged in blocks of four. In this assessment, the participant is provided with a set of four pictures and the
experimenter provides the participant with a sentence (e.g. *The comb is red*). The participant then is required to point to one of the four items that they consider is describing the sentence provided by the experimenter. Items are organized in ascending order based on difficulty level. Participants are tested on 20 grammatical concepts. The test typically takes between 10 to 20 minutes to administer.

**Vocabulary.** The Peabody Picture Vocabulary Test – Fourth Edition (PPVT–4; Dunn & Dunn, 2007) is standardized measure of receptive vocabulary that is suitable for individuals between the ages of 2 years, 6 months through 90 years and older. The PPVT–4 is made up of 228 items grouped into 19 sets of 12 items each. The items are arranged in an order of increasing difficulty. During the assessment, participants are provided with a set of four pictures, where the examinee is required to point to one of the four picture that best illustrates the word that is provided by the examiner. For example, if the participant is provided with pictures of: a zipper, a tie, a shirt, and a belt, the experimenter asks: “Can you point to *adjustable*?”, after the participant points to the picture that he or she thinks reflects the word adjustable (i.e. belt) the examiner proceeds to the next page. This assessment is terminated if the participant makes 8 mistakes in one set. The test typically takes between 10 to 20 minutes to administer.

**Nonword repetition.** A computerized version of the nonword repetition task was used (Munson, Kurtz, & Windsor, 2005; Edwards, Beckman, & Munson, 2004). The task was run on an Acer Laptop using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). The task comprised of 30 three and four syllable nonwords recorded by a female English speaker. The nonwords were divided into two blocks. Each nonword was presented auditorily, with stimulus randomization within the two blocks. Participants were asked to repeat each nonword back as soon as a blue cross fixation symbol appeared on the computer screen. All responses
were audio recorded. All responses were scored based on correct vs. incorrect using a binary system for right and wrong responses. The mean arcsine proportion score was used as the predictor variable.

**Assessments of nonverbal abilities.**

*Nonverbal intelligence.* The Test of Nonverbal Intelligence – Third Edition (TONI–3; Brown, Sherbenou, & Johnsen, 1997) is a language-free assessment that is suitable for individuals between the ages of 6 and 89 years and 11 months. It is a measure of intelligence, aptitude, abstract reasoning, and problem solving. The test consists of 60 items arranged in order of increasing difficulty. Participants are presented with a series of shapes that are set in a specific pattern. Participants are then required to choose from a series of four to six shapes the shape that best completes the pattern. The test typically takes between 15 to 20 minutes to administer. Assessment is terminated after 3 mistakes are made in a series of five consecutive items.

**Sequence learning.** To measure sequence learning we used a children’s version of the Nissen and Bullemer’s (1987) Serial Reaction Time (SRT) task (Lum et al., 2010). The task was run on an Acer Laptop using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). A standard PC game pad with a USB interface was used for participants’ responses. All reaction time data were recorded using the E-Prime 2.0 software. The program started with a message that read “Welcome to the Smiley Face Game”. Then an instruction page was provided (see Figure 1), followed by practice trials where the researchers showed the participant the mapping between the visual stimulus and response buttons on the gamepad. The participant was then provided with 10 practice items. Participants were instructed to press the button on the gamepad that matches the location of the visual stimulus, smiley face, on the computer screen (see Figure 1). Feedback was given on each practice trial. The practice trial was followed by a test trial
where the participant was provided with a 10-item repeating sequence that was presented over four blocks of 60 trials. In the final block the smiley face appeared in a random sequence for another 60 trials. Learning in the SRT task is traditionally measured by assessing reductions in RTs for blocks of trials following the fixed sequence, as compared to blocks of trials following a random sequence (Random Block – Block 4), i.e. rebound effects (Nissen & Bullemer, 1987; Robertson, 2007).

Figure 1. Example of Trials in the Serial Reaction Time task (Lum et al., 2010)
**Motor Coordination.** The Grooved Pegboard (Lafayette Evaluation, Lafayette Instruments # 32025) was employed as a measure of fine motor coordination. The pegboard consists of 25 key-shaped holes arranged in a five by five matrix (see Figure 2). Below the grid of holes is a circular receptacle where the key-shaped pegs are placed. Children were asked to use their dominant hand and place all the pegs in the appropriate hole. They were required to rotate the peg to match the hole before it is inserted. Using a stopwatch, the researchers timed how long it took each participant to complete this task. Scores in seconds were recorded for performance using the dominant hand.

![Figure 2. The Grooved Pegboard Task Used in this Study (Lafayette Evaluation, Lafayette Instruments # 32025, image retrieved from: https://lafayetteevaluation.com/products/grooved-pegboard)](https://lafayetteevaluation.com/products/grooved-pegboard)
**Working memory.** The array memory task (Cowan, AuBuchon, Gilchrist, Ricker & Saults, 2011) was adapted and used as a computerized measure of working memory. The task was run using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). In this task, participants were instructed to attend to a series of colored circles that appear in a grid of 12 squares (see Figure 3). After the grid appeared with several circles, it disappeared and appeared again with a single circle. Participants were required to decide where the stimulus belonged. To keep the children interested, the task was presented as a classroom scenario with the circle shapes representing children and participants were instructed to click the box (seat) in which the colored circle (child) belonged and if that circle (child) did not belong anywhere in the classroom, a door icon should be clicked “sending the circle (child) to the principal”. All responses were scored based on correct vs. incorrect using E-Prime 2.0. The mean arcsine proportion score were calculated and used as the predictor variable.

![Example of Trials in the Array Memory Task](image)

Figure 3. *Example of Trials in the Array Memory Task (Cowan et al., 2011)*
CHAPTER 6

Results

Analytic Plan

Trained research assistants scored data for all 63 participants. The data from the SRT and Array Memory tasks were scored by the E-Prime. All standardized assessments were double-checked for accuracy of scoring. Inter-rater reliability was calculated for the scoring of the nonword repetition task. Data were scored for 20% of the sample, which was 13 participants (390 trials). All disagreements were resolved through discussion. Inter-rater reliability was above 94%. To address each of our research questions we conducted several multiple regression analyses to explore relationships between individual differences in sequence learning, motor coordination and language abilities (grammar, vocabulary, phonology) and nonverbal intelligence. Table 1 (see above) provides the means and standard deviations on all predictor and outcome variables. Our participants showed a wide range of outcomes indicating considerable differences in children's linguistic, motor, and cognitive abilities.

Analyses

Preliminary analyses. All data were checked for skewness and kurtosis. The accuracy on Block 1 variable was skewed (skewness: $M = -2.83; SD = .30$; kurtosis: $M = 8.27, SD = .59$). Arcsine transformations were applied for the variables that were proportion scores: the nonword repetition task, the Array Memory Task, and accuracy on Block 1 of the SRT task (Cohen & Cohen, 1983). Z-scores were computed for the reaction time (RT) data extracted from the SRT task. No other variables needed data transformation.
Preliminary correlations were conducted to examine the associations between age, gender, child's handedness, and our predictor and outcome variables (predictor variables: sequence learning, motor coordination; outcome variables: grammar, vocabulary, phonology). Preliminary analyses showed that age and was correlated with all of the language assessments, $p < .001$. Gender was not associated with differences in language abilities, $p > .12$. Handedness was also not associated with any of our variables of interest, $p > .07$. When controlling for age, nonverbal working memory was correlated with the pegboard task, $r = -.26$, $p = .04$, and some of our outcome variables of interest (PPVT: $r = .24$, $p = .06$; TROG: $r = .29$, $p = .03$; Nonword repetition: $r = .10$, $p = .43$). Due to these significant associations and to research showing that working memory plays an important role in children's language development, all further analyses controlled for working memory (Leonard et al., 2007). We also computed the Pearson correlation coefficients between all our predictor variables (sequence learning, measures of motor coordination) together to confirm that multicollinearity is not an issue and that these variables can be placed together in a regression model (see Table 2). We then ran correlations between our predictor variables (grammar, vocabulary, phonology) to confirm associations that have been reported in the literature (see Table 3).

**Are the kids learning the sequences?** Figure 2 displays the children’s RT scores on the SRT task from the first sequenced block that they were exposed to the last random block. The percentage values on top of the line graph are the children's average accuracy scores on each block, i.e., the percentage of times they clicked the correct button in relation to the location of the smiley face on the screen. Prior to running analyses on any of the sequence learning data, we transformed each participants median accurate Reaction Time scores into $z$-scores. We then computed the sequence learning variable by subtracting $z$-scores on Block 4 of the SRT task.
from their z-scores on the final random block (M = .12, SD = .25). To examine whether the children learned the sequences, a paired-samples t-test was used to compare whether significant reductions were observed between the final sequenced block compared to the first random block. T-test analyses revealed that there was a significant difference between children’s performance on Block 4 (M = 717 ms, SD = 190) and their performance on the random block (M = 754 ms, SD = 184, t (62) = −4.00, p < .001), suggesting that the children learned the sequences.

Figure 4. Participants’ Performance on the SRT Task across Sequenced and Random Blocks

Alternative Measures of Motor Coordination. Accuracy on the SRT task was high with many children performing at ceiling, most of the children did not make any errors when it came to "catching the smiley face", however, we noticed that some children found it difficult to manipulate the gamepad and click on the appropriate button that matches the location of the smiley face on the screen, which suggested some motor difficulties. For this reason, we extracted accuracy data on Block 1 of the SRT task as a possible novel and additional measure of
children’s fine motor abilities (M = 91.6%, SD = 13.6%, Range: 35% – 100%). We then transformed this data into a mean arcsine proportion score.

**Assessing Predictor and Outcome Variables.** Partial-correlations were computed between all predictor variables. The pegboard task was shown to be correlated with measures of accuracy on Block 1 of the SRT task indicting that the faster the child is on the pegboard the more accurate they are on Block 1 of the SRT task even after controlling for age and working memory, \( r (59) = -.34, p = .003 \). Neither the Pegboard task not Accuracy of Block 1 were correlated with sequence learning, \( p > .46 \). To avoid possible issues of multicollinearity, the Pegboard task was not put in any regression models with the accuracy on Block 1 measure.

Table 2 shows correlations between all outcome measures. As expected, all our outcome measures were highly correlated with one another. To avoid issues of multicollinearity and in order to examine the individual contributions of each language measure in relation to our predictor variables, we ran separate regression analyses with each outcome variables entered in separate analyses.

**Table 2**

**Partial Correlations Controlling for Age between Outcome Variables**

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vocabulary (PPVT)</td>
<td>.67***</td>
<td>.49***</td>
<td>.38**</td>
</tr>
<tr>
<td>2. Grammar (TROG)</td>
<td>1</td>
<td>.45***</td>
<td>.56***</td>
</tr>
<tr>
<td>3. Phonology (Nonword Repetition)</td>
<td>1</td>
<td>.12</td>
<td></td>
</tr>
<tr>
<td>4. Nonverbal Intelligence (TONI)</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

*Note: *** p < .001, ** p < .01*
**Sequence learning, motor coordination, and language.** To determine which of the predictor variables (sequence learning, motor coordination) had an effect on our outcome measures, we used simultaneous regression analyses to examine the relationship between motor coordination measures, sequence learning, and language abilities in children. In our first regression model, we entered control variable (age in months, and working memory), motor coordination variable, and our traditional measure of sequence learning all in one step. We then ran regression models on each language assessments separately (vocabulary, grammar, phonology). These results are presented in Table 3. Collinearity diagnostics indicated that all VIFs were below 1.4 and tolerance values were above .2 indicating that multicollinearity is not an issue among our variables. Observation of P-P plots showed that the assumption of normality has been met (Field, 2009).

These analyses show that motor coordination (measured using the pegboard task), but not our traditional measure of sequence learning, was predictive of all measures of language (vocabulary, grammar, and phonology). The findings show that the faster a child is at the pegboard task the better they are at measures of language assessment with our model accounting for 21% to 35% of the variance in language scores (see Table 3).
Table 3

Standardized Regression Coefficients Obtained from Multiple Regressions with Age, Working Memory, Sequence Learning, and Motor Coordination as Predictor Variables

<table>
<thead>
<tr>
<th></th>
<th>Vocabulary (PPVT)</th>
<th>Grammar (TROG)</th>
<th>Phonology (Nonword Repetition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in months</td>
<td>.30*</td>
<td>.05</td>
<td>.94</td>
</tr>
<tr>
<td>Working Memory</td>
<td>.15</td>
<td>.22</td>
<td>.02</td>
</tr>
<tr>
<td>Sequence Learning</td>
<td>.10</td>
<td>.02</td>
<td>−.11</td>
</tr>
<tr>
<td>SRT Rebound Effect</td>
<td>−.27*</td>
<td>−.31*</td>
<td>−.38**</td>
</tr>
<tr>
<td>Motor Coordination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Pegboard)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$ total</td>
<td>.35</td>
<td>.22</td>
<td>.21</td>
</tr>
<tr>
<td>Model F (4, 58)</td>
<td>7.78***</td>
<td>4.13**</td>
<td>3.94**</td>
</tr>
</tbody>
</table>

Note: *** $p < .001$, ** $p < .01$, * $p < .05$

Results of our regression analyses show that motor coordination is associated with multiple aspects of language and cognitive ability (vocabulary, grammar, and nonword repetition). However, we were unable to support views linking language skills with sequence learning using a traditional learning measure from the SRT task. As the children were completing the sequence learning task, we noticed that accuracy was at ceiling with some children struggling with catching the smiley face, for this reason and as post-hoc analyses, we decided to examine whether individual differences in accuracy on the first block of the SRT task (when children are exposed to this task early on) could detect individual differences in language abilities and tease out the children who are finding this simple task challenging. For this reason, we used an arcsine transformation of accuracy on Block 1 of the SRT task (which we called an alternative or nontraditional measure of motor coordination). We entered control variable (age in months and nonverbal working memory) and accuracy on block 1 of the SRT in the regression model. We then ran regression analyses on each language assessment separately (vocabulary,
grammar, phonology). These results are presented in Table 4. Collinearity diagnostics indicated that all VIFs were below 1.4 and tolerance values were above .2. P-P plots showed that the assumption of normality has been met (Field, 2009).

These post-hoc analyses showed that individual differences on accuracy on Block 1 of the SRT task was associated with both vocabulary and grammar, but not phonology. Results showed that the more accurate the child was on Block 1 of the SRT task, the better their grammar and vocabulary scores (see Table 4). Results show that the pegboard task (a frequently used measure of fine motor coordination) was robustly predictive of all aspects of language. Our attempts to use a second nontraditional measure that may tap into fine motor coordination in children (accuracy on Block 1 of the SRT) showed that the significant findings between this simple measure and language abilities suggests that children who really struggled with being able to catch the smiley were also the children who struggled in language. In other words, our accuracy measure seems to be a good predictor of both vocabulary and grammar, while children were generally highly accurate on this task there was a large range (35% to 100%), this task seems to be picking up the participants who are struggling on a relatively simple task (the outliers) and these children seem to be the ones who are also struggling in language. In the upcoming sections we run further outlier analyses to assess this claim.
Table 4

*Standardized Regression Coefficients Obtained from Multiple Regressions with Age, Working Memory, and SRT accuracy as Predictor Variables*

<table>
<thead>
<tr>
<th></th>
<th>Vocabulary (PPVT)</th>
<th>Grammar (TROG)</th>
<th>Phonology (Nonword Repetition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in months</td>
<td>.31†</td>
<td>.03</td>
<td>.19</td>
</tr>
<tr>
<td>Working Memory</td>
<td>.17</td>
<td>.21†</td>
<td>.07</td>
</tr>
<tr>
<td>SRT Block 1 Accuracy</td>
<td>.25*</td>
<td>.36**</td>
<td>.17</td>
</tr>
<tr>
<td>( R^2 ) total</td>
<td>.33</td>
<td>.25</td>
<td>.12</td>
</tr>
<tr>
<td>Model ( F (3, 59) )</td>
<td>9.67***</td>
<td>6.51**</td>
<td>2.60†</td>
</tr>
</tbody>
</table>

*Note: *** \( p < .001 \), ** \( p < .01 \), * \( p < .05 \)*

**Nonverbal skills and measures of sequence learning and motor coordination.** Our results showed that motor coordination is associated with language measures (grammar and vocabulary) in addition to phonological skills in children (nonword repetition). Our findings linked motor coordination to verbal measures of language and cognition. We wondered whether motor coordination is important in nonverbal skills as well, or whether such a finding is restricted to linguistic aspects of development. We sought to explore this post-hoc research question and assess whether motor skill is significant at predicting not only children's verbal abilities, but also their nonverbal abilities. To determine whether nonverbal intelligence played a role in motor coordination we ran regression analyses and entered our control variable (age in months and working memory) and the pegboard task all in one model. All assumptions were met. Our model was significant, \( F (4, 59) = 8.32, p < .001 \) with age (\( \beta = .27, p = .03 \)) and motor coordination (\( \beta = -.27, p = .03 \)), but not working memory (\( \beta = .15, p = .24 \)) explaining 27.0% of the variance in non-verbal intelligence, suggesting that the faster the child was at the pegboard task the higher their scores on the nonverbal intelligence assessment.
In order to attempt to replicate this same finding using the nontraditional and novel measures of motor coordination, we used regression analyses and entered the control variables (age in months and working memory) and accuracy on block 1 of the SRT task. We then ran a regression analysis with nonverbal intelligence entered as a predictor variable. All assumptions were met with VIFs were below 1.4 and tolerance values were above .2 (Field, 2009). P-P plots also showed that the assumption of normality was assumed. Results showed that age (β = .30, \( p = .02 \)) as a control variable significantly predicted change in nonverbal intelligence, however, working memory (β = .19, \( p = .13 \)) and accuracy on Block 1 (β = .16, \( p = .20 \)) were not significantly associated with scores on our measure of nonverbal intelligence. The model explained 26.6% of the variance in nonverbal intelligence, \( F(3, 62) = 7.14, \ p < .001 \). Our findings suggest that motor coordination plays a critical role in both verbal and nonverbal aspects of children's abilities. However, the pegboard task was the most robust predictor of such effects. These findings were not replicated using our novel and nontraditional measures of accuracy on the SRT task.

**Outlier analyses.** As a next step to understanding the role of motor coordination in relation to individual differences in language abilities, we conducted further outlier analyses to understand what is driving our significant results.

**Removing the children with low-language scores.** As a first step, we removed children who had language assessment scores that were one standard deviation below the mean (less than 85 on the CELF total) and we reran the regression model with age, working memory, sequence learning, and motor coordination in the model. We ran regression analyses on each language assessments (vocabulary, grammar, phonology) and nonverbal intelligence separately. Results showed that when we removed the low scoring children, performance on the pegboard was not
significantly associated with any of our language measures, \( p > .18 - .79 \). Performance on the pegboard task was also not associated with scores of nonverbal intelligence, \( p = .11 \). These findings speak to the fact that the children who have low language scores are also the children who take longer to complete the pegboard task. This shows that the children with low language scores are driving the significant findings that we have discussed above.

We then reran the same analyses with the SRT accuracy variable, where age and working memory along with the accuracy arcsine variable were entered into the regression model. We then ran separate regression analyses on each language assessments separately (vocabulary, grammar, phonology) and nonverbal intelligence. Results showed that, here also, all our accuracy findings were no longer significantly associated with any of our outcome language measures, \( p = .11 - .57 \), nor were they significant with nonverbal intelligence, \( p = .55 \), suggesting that the children who had lower language scores were driving the effects in a significant direction.

**Removing the children with high language scores.** In order to confirm this finding, we removed the children with high language scores (1 SD above the mean, i.e. scores on the CELF total that were higher than 115) from the analyses. If it is true that the children with lower language scores are driving the effects between fine motor coordination, then we would expect that keeping the low-scoring children and removing the children with high language abilities would not affect any of our findings and motor coordination will remain associated with all language and nonverbal intelligence measures. We ran the regression analyses with age, working memory, sequence learning, and motor coordination in the model. We then ran regression models on each language assessments separately (vocabulary, grammar, phonology) and nonverbal intelligence. Results showed that when the children with high language scores were
dropped from the analyses, performance on the pegboard task remained significantly associated with all language measures, $p = .02 - .04$, however, no relationship was found between performance on the pegboard and nonverbal intelligence, $p = .12$. However, when accuracy on block 1 of the SRT task was used as a predictor variable, performance on this task being was only associated with individual differences in grammar, $p = .02$, but not vocabulary, $p = .09$, phonology, $p = .21$, or nonverbal intelligence, $p = .20$.

**Sequence learning: Using a non-traditional measure.** The majority of the literature measures learning in the SRT task by computing RT differences for sequenced versus random blocks (e.g., Nissen & Bullemer, 1987; Lum et al., 2014), which is the approach we adopted in this current study to run all analyses. However, in a recent meta-analysis, Foti and colleagues (2015) measured learning in the SRT tasks by examining reductions in RTs across sequenced blocks. In order to assess whether sequence learning, as measured by Foti et al. (2015) might be a more accurate individual differences assessment of children's learning of the sequences, we computed a new variable where we subtracted performance on the last sequenced block and performance on the first sequenced block and computed a $z$-score variable ($M = -.09$, $SD = .34$). We then ran partial-correlations between this non-traditional sequence learning measure and our language and nonverbal intelligence variables while controlling for age and working memory. Results from the correlational analyses showed that sequence learning, measured in a non-traditional manner, was not associated with any of our outcome variables of interest ($p = .16 - .85$).
CHAPTER 7

Discussion

Theories of language development have long been divided between approaches of single and dual route mechanisms of language acquisition, with some theories suggesting that we learn grammar and vocabulary according to different learning trajectories and others arguing for a single route of *all* aspects of language learning. Single-route approaches to language development also adopt a domain-general approach suggesting that children's development of language abilities is also associated with other aspects of development, including motor and gestural development (Bates & Dick, 2002). Conversely, and in line with the dualistic approach, is the procedural deficit hypothesis (Ullman & Pierpont, 2005) that suggests that impairments in rule-based aspects of language may be due to an underlying impairment in procedural/sequence learning. This theory suggests that sequence learning is related to the learning of rules in language (i.e. grammar, phonology) but not word learning (i.e. vocabulary). In line with the procedural deficit hypothesis, meta-analyses have shown sequence learning impairments in children with Specific Language Impairment (SLI; Lum et al., 2014) and Dyslexia (Lum et al., 2015). However, children's phonological skills (which according to the PDH is procedural in nature) have been linked to their vocabulary size and word learning abilities (Gathercole et al., 1992). This led us to question whether, in line with the PDH, tasks of sequence learning are sensitive at detecting individual differences in grammar and phonology but not vocabulary in children, or whether all aspects of language are inter-related with one another.

Furthermore, the procedural/declarative model suggests that motor skills and sequencing abilities are both associated with procedural memory (Ullman, 2004), which may implicate that some language abilities (i.e. rule-based) may be associated with motor skill. More central to the
idea that motor and language abilities co-develop is the work of prominent theorists such as Piaget who stresses the development of both verbal and nonverbal symbols as children advance through what he termed the "sensorimotor stage" (Bates & Dick, 2003; Bates & Snyder, 1987; Beard, 2006; Karmiloff-Smith, 1995; Piaget, 1999). In line with this domain-general merge between multiple aspects of development, other theories of child development have emphasized links between motor and language development in early childhood (Diamond, 2000; Iverson, 2010; Iverson & Thelen, 1999). Researchers have been able to document associations between the co-development of language and motor skills among infants, yet few studies have explored whether these relationships persist into the school years. Furthermore, relationships between motor and language development are well documented in clinical studies (Leonard & Hill, 2014), as children with SLI and other developmental disabilities often exhibit concomitant fine- and gross-motor impairments. In line with theories linking motor coordination and various aspects of language development, we were interested in looking at the role that fine motor coordination plays in children's verbal abilities. We then wanted to assess whether motor coordination not only predicted language measures but was also associated with children's nonverbal abilities.

To examine the role of sequence learning and motor coordination in language and cognitive development, we administered a battery of language and cognitive assessments to a diverse community sample of 63 children (33 girls, 30 boys), mean age 8 years; 2 months (SD 1;3). We employed a commonly used measure of sequence learning, in addition to the pegboard task to examine motor coordination. We also examined children's nonverbal working memory. We also used a series of standardized language and nonverbal intelligence assessments, in addition to the nonword repetition task as a measure of phonology.
Research Question 1. Sequence Learning and Language

Are individual differences in sequence learning related to language abilities? In particular, will there be a specific relationship between rule-based aspects of language (e.g., grammar, phonology) and sequence learning?

We were interested in examining whether a relationship exists between sequence learning and individual differences on assessments of language, in particular, whether there will be a distinction between rule-based and fact-based aspects of language in relation to sequence learning. Using a traditional measure to assess sequence learning, our findings did show that on average, the children learned the sequences in the SRT task, however, regression analyses found no associations between grammar and sequence learning. This finding was not in line with our initial hypothesis attempting to support the PDH and suggesting that we would find significant associations between sequence learning and children's grammatical abilities (but not vocabulary). However, we also did not find a significant relationship between sequence learning and children's receptive vocabulary. This has been initially what we expected to find, but such confirmatory non-significant findings need to be analyzed with caution considering sequence learning was not associated with any of our variables of interest. Chapter 8 discusses possible limitations why that might have been the case. Furthermore, looking at nonword repetition as a measure of children's phonological skills, we expected to find associations between sequence learning and performance on nonword repetition. However, our measure of sequence learning was not associated with the children's abilities to repeat back multisyllabic novel nonwords.
Research Question 2. Motor Coordination and Sequence Learning

In line with the procedural/declarative view of language and motor development. Will a relationship exist between measures of motor coordination and measures of sequence learning?

Theories of procedural/declarative memory (Squire & Zola, 1996; Ullman, 2004) suggest that sequence learning and motor skills are both part of the procedural memory system, from this theory, we expected to find relationships between our measures of motor coordination and our task of sequence learning. We did not find any significant associations between these measures. This is not to say that these two areas of development are not associated in one way or another, and one must not be quick to dismiss such a relationship. It remains that further research is needed to examine whether a relationship between sequence learning and motor measures exists while using different tasks to measure sequence learning.

Research Question 3. Motor Coordination and Language

Are individual differences in fine motor skills related to language abilities? If so, what aspects of language abilities is particularly related to fine motor coordination (words versus rules)?

In line with the theory that rules of language are learned through procedural learning (Pinker, 1998; Ullman, 2004) and because motor skill is related to procedural learning, we sought out to examine whether rule-based aspects of language would be associated with measures of motor coordination. We found associations between measures of grammar and motor coordination showing that the better the child is at tasks of motor coordination (the faster and more accurate) the better their scores on grammatical assessments. We also found
associations between children's motor abilities and their performance on the nonword repetition task, suggesting that the better the child is at a task of fine motor coordination the more accurate they were at repeating nonwords. However, we also found correlations between measures of vocabulary and motor coordination. Our findings linking grammar and nonword repetition to motor coordination were in line with our hypotheses and partially in line with the PDH, however, we did not expect to find such associations with vocabulary as the literature remained mixed. Furthermore, our finding that motor coordination plays an important role in nonword repetition might be in line with the procedural model linking motor skill to rule-based aspects of language, but also speaks to the idea that cognitive and motor skills in children are not distinct aspects of development but rather highly intertwined (Diamond, 2000). Our finding that both these aspects of language (both rule-based and word-based) are associated with motor coordination seems to be more in line with theories adopting a single-route approach to language acquisition, as there does not seem to be a distinction between grammatical and vocabulary abilities in children (see Bates & Goodman, 1997). Our results offer support to theories indicating that the development of motor and cognitive/linguistic areas in children are fundamentally intertwined and that these two areas of development should not be regarded as separate fields of study (Diamond, 2002; Iverson, 2010). Our research offers support for domain-general theories of language development that highlight the importance and co-development of both verbal and motor aspects of development in children (e.g., Bates & Dick, 2002; Thelen & Bates, 2003; Iverson & Thelen, 1990).

As a post-hoc hypothesis and after finding links between motor coordination and various language and cognitive assessments. We extracted one other fine motor assessment in attempts to replicate our findings linking language measures to motor coordination. Our results showed that
the pegboard task, as a traditional measure of fine motor coordination, was the strongest predictor of grammar, vocabulary, and phonological skills in children. However, accuracy on the first block of the SRT task was also associated with both grammar and vocabulary, but not phonology. It is noteworthy that accuracy on Block 1 of the SRT task, while a relatively simple task where children ceiling effects (M = 92%), there was a large range in accuracy scores (32%-100%). Thus, the task was successful at detecting the children the children who were "outliers", i.e. those who struggled with simple fine motor tasks and also seemed to struggled with language.

Research Question 4. Nonverbal Skills and Measures of Sequence Learning and Motor Coordination

Are individual differences in sequence learning and fine motor coordination related to non-verbal abilities?

This research question was developed after we found relationships between motor coordination and verbal measures. We were interested in looking at whether the relationship between motor coordination was associated with not only verbal measures, but also nonverbal cognitive skills. Our findings showed that performance on the pegboard task was related to children's nonverbal intelligence, however, we were unable to replicate these findings when using a nontraditional motor measure (accuracy on Block 1 of the SRT). Even though our findings were not successfully replicated, our initial results with the pegboard task do show that motor coordination is important in both, children's verbal and nonverbal abilities. Our research sheds light and offers support to theories which suggest that motor coordination is not really a
separately acquired developmental skill but rather critical in children's language and cognitive development as well (e.g., Iverson, 2010).
CHAPTER 8

General Discussion and Implications

In this study, we set out to examine the role of sequence learning and motor coordination (aspects of procedural memory) as predictors of multiple language and cognitive abilities in a community sample of typically developing children who range in linguistic abilities (from language impaired to linguistically precocious). We realized that a majority of the literature has adopted an extreme-group design or group-level analyses to look at variations in abilities between language impaired children and their typically developing peers. However, while group-level analyses answer many questions that researchers pose, adopting an individual differences approach seems critical for this study design because we were interested in answering questions pertaining to direct associations between our variables of interest. Furthermore, some problems arise when using an extreme group design, such as assuming that participants in each group are homogenous in abilities (which is highly unlikely). Furthermore, the use of extreme group design increases the possibility of making a Type 1 error (Conway et al., 2005; Preacher et al., 2005; Unsworth et al., 2015). For this reason, we adopted an individual differences approach to answer our research questions. We collected data from 63 children in order to assess the role of individual differences on various predictors (sequence learning, motor coordination) in relation to children’s abilities on a range of language measures (vocabulary, grammar, and phonology). In the upcoming sections, we will discuss our findings in light of previous literature.
Sequence Learning and Language Development

It is safe to say that language acquisition is highly complex and multi-factorial. There has been considerable debate in the literature regarding how children acquire language; some theorists posit that the learning of rule-based aspects of language is restricted to the procedural memory system, whereas our knowledge of word meaning is linked to the declarative memory system where most factual knowledge is housed (e.g. Pinker, 1998; Ullman, 2004). The procedural deficit hypothesis was influenced by the dualistic-view towards language development, and suggests that children who show difficulties in rule-based aspects of language also show deficits in procedural/sequence learning in particular, but their declarative memory remains largely intact (Ullman & Pierpont, 2005; Ullman, 2004). In line with the PDH, several studies have supported the view that children with language impairments show difficulties in sequence learning (see Lum et al., 2014; Lum et al., 2013 for meta-analyses). Furthermore, the procedural/declarative theory suggests that motor skill and sequence learning are related and both occur in the procedural memory system and thus one would suspect that these two skills are highly associated with one another, with motor skill being related to rule-based aspects of learning, as well as sequence learning. In addition to sequence learning and motor coordination in language development, the language literature has focused on the role of phonological short-term memory as a possible underlying deficit in language impairment with robust support for the nonword repetition task as clinical marker for SLI. A typical nonword repetition task tests children's phonological abilities; in line with the PDH phonology is associated with knowledge of the rules of the sounds of a language and hence is assumed to be related to procedural/sequence learning (Ullman, 2004). However, performance on the nonword repetition task has also been consistently associated with vocabulary size and acquisition, a relationship
that has been deemed bidirectional (Goodman, 2006). This literature suggests that sequence learning and motor coordination may be associated with language assessments of vocabulary, grammar, and phonology.

**Sequence learning and grammar.** We originally set out to examine the associations between sequence learning and language abilities in children. We had hypothesized that performance on tasks of sequence learning would be associated with measures of grammar among school-aged children. We hypothesized that in line with the procedural model, no relationship should exist between vocabulary size and sequence learning since vocabulary acquisition is thought to occur via declarative memory systems (Ullman, 2004). We did not find relationships between sequence learning and any language measure, including grammar, phonology, and vocabulary. This suggests that we were unable to find support for our initial hypothesis linking sequence learning to grammatical ability. This is not in line with Tomblin et al.'s (2007) research showing that when children with SLI are divided based on grammatical ability (but not vocabulary scores) the grammar impaired group shows significant difficulties on performance on the SRT task compared to peers. Furthermore, our findings are not in line with Kidd (2012) who found that children who showed higher sequence learning (measured using the SRT task) were able to produce complex passive sentences when primed. However, the relationship between sequence learning and grammatical abilities in children is far from clear-cut considering that some researchers (that also used the SRT task) were unable to find any significant relationships between performance on the SRT task and measures of grammar. For instance, two other studies by Kidd (Kidd & Kirjavainen, 2011; Lum & Kidd 2012) did not find associations between measures of past-tense use and performance on the SRT task. Our nonsignificant findings between sequence learning and language measures do seem to be in line
with the majority of the results of individual differences research adopting the same SRT task that we employed. However, the literature linking sequence learning to grammatical abilities seems to be inconsistent largely due to the wide array of tasks that propose to measure sequence learning, but in reality may be measuring distinct and unrelated constructs (Siegelman et al., 2016).

**Sequence learning and vocabulary.** We did not find significant relationships between sequence learning and children's vocabulary size. While this seems to be in line with the PDH, which suggests that the learning of vocabulary and grammar are unrelated, this is not in line with theories proposed by infancy researchers who link sequence learning to word learning in children. For instance, Evans et al. (2009) found that performance on a speech stream task was associated with children's receptive and expressive vocabulary. Other research with infants also showed associations between vocabulary ability and performance on sequencing tasks (Shafto et al., 2012; Estes et al., 2007). It is important to note that none of the literature that has shown significant associations between vocabulary and sequence learning has not used the SRT task but rather employed various versions of Artificial Grammar Learning or speech stream tasks, which typically employ verbal stimuli while assessing sequence learning. Research has found that the various tasks used in the literature, which are all presumed to be measuring sequence learning (e.g., SRT, SS, AGL) seem to show small to non-significant correlations amongst each other (Siegelman & Frost, 2015). Since these different tasks of sequence learning are uncorrelated with one another, it is difficult to link our nonsignificant findings between sequence learning (measured using the SRT task) and vocabulary ability to a body of literature looking at a completely different range of seemingly unrelated tasks (AGL and speech stream). Furthermore, while we found nonsignificant relationships between sequence learning and vocabulary size, we
cannot immediately say that our hypothesis suggesting that no relationship will exist between sequence learning and vocabulary has been confirmed; results from our measure of sequence learning need to be interpreted with caution considering that none of our variables were associated with our measure of sequence learning and the task produced nonsignificant findings across the board implying that it may not be ideal at detecting individual differences.

**Sequence learning and phonology.** Nonword repetition is a unique task that taps into individuals’ phonological skills and their short-term memory abilities. This task has gained interest over the years as a clinical marker for SLI. Studies have linked performance on the nonword repetition task to children's vocabulary abilities (Gathercole, 2006). Further research has shown that children with SLI perform worse compared to typical peers on various versions of nonword repetition (Estes et al., 2007). In line with the PDH hypothesis, which links impairments in procedural learning as an underlying cause to language impairment and because children with SLI typically show phonologically-related deficits, we assumed that performance on a task of sequence learning would be correlated with measure of phonology in children. Similar to our findings with grammar and vocabulary (but not in line with our hypotheses) performance on the SRT task was not associated with phonology. Thus, suggesting that children's phonological skills are unrelated to sequence learning. However, before we are able to make such a strong claim and since none of our language measures were associated with sequence learning, we suspect that the SRT task, which has been so commonly used in group-level research, is incapable of detecting individual differences in the general population. This directly speaks to Siegelman et al.’s (2016) research where they discuss limitations of currently available tasks of sequence learning suggesting that the currently available measures in the
literature may be psychometrically weak and flawed. These limitations might underlie why none of our sequence learning findings were significant and will be discussed later on in this chapter.

**Motor Coordination and Language Development**

Children's language and motor development are two of the most important areas of child development, while these areas have been regarded as two separate disciplines under developmental science, some researchers suggest that these two areas are more aligned than we have previously presumed (see Diamond, 2000; Iverson, 2010). The previous section discussed language development in light of the procedural/declarative view of learning, however, our data did not offer support for this view. Opposing this dualistic theory of language development is a more historically accepted view of a domain-general approach to child development. This view stemmed from the work of great theorists in the field of developmental psychology such as Piaget, Vygotsky, and Dewey. All these theorists discuss the importance of both the body and the mind in children's development. Coming out of these approaches that view the child as developing within his or her environment, is the embodiment perspective that emphasizes the crucial importance of the child's body (such as their motor abilities) in relation to the development of cognition (see Thelen & Bates, 2003; Iverson & Thelen, 1999). In support of this unification between motor and language development, Elizabeth Bates and colleagues (Bates & Dick, 2002; Bates & Goodman, 1997; Volterra et al., 2005) offers evidence for the co-development of language and gesture in children. Similarly, Diamond (2000) offers a neurodevelopmental perspective and highlights the role of common brain areas, such as the cerebellum, in the development of both motor and cognitive functioning. Thus, domain-general theories to child development have discussed the importance of examining language and motor abilities as two intertwined areas of child development (see Diamond, 2000; Iverson, 2010).
There is a plethora of clinical research linking language impairments to concomitant difficulties in fine motor coordination and motor skills (e.g., Leonard & Hill, 2014). While there is clinical literature linking language impairment to difficulties in motor coordination, the individual differences literature looking at direct associations between cognitive/language abilities and motor coordination remains limited (Davis et al., 2011; Roebers et al., 2014). For this reason, we attempted to use an individual differences approach to answer questions pertaining to the relationship between motor coordination and specific measures of language and cognition.

We were interested in examining direct associations between motor coordination and grammar, vocabulary, and phonology in school-aged children. Prior to doing so, we hypothesized that since sequence learning and motor skill were both part of the procedural memory system (Ullman, 2004) then they would be correlated with one another. This finding was not supported as none of our variables were significantly associated with sequence learning possibly because we used a measure that is not sensitive to individual differences (Siegelman et al., 2016).

We then moved on to examine whether motor coordination would be associated with measures of grammar and phonology, but not vocabulary. Our initial measure of motor coordination was predictive of all aspects of language (grammar, vocabulary, and phonology). This was in line with the majority of the clinical literature suggesting that children with language impairments are those children that also show difficulties in fine motor coordination (Houwen et al., 2016; Owen & McKinlay, 1997). The individual differences literature remains rather limited, however, our findings that relationships exist between all measures of learning and motor coordination seems to be in support of the currently available literature. For instance, Oudgenoeg-Paz et al. (2012) found significant relationships between children's walking and their
vocabulary development between the ages of 16 and 28 months. Furthermore, maternal questionnaires have shown relationships between children's communicative and motor abilities with motor skills at a younger age predicting communication abilities in children at the age of three (Wang et al., 2012). Furthermore, deficits in motor coordination proved to be associated with low language abilities among preschoolers (King et al., 2015). To our knowledge, there does not seem to be any research linking children's performance on nonword repetition (a clinical marker of SLI) to measures of fine motor coordination, the literature in that area is restricted to links between nonword repetition and measures of articulatory coordination (Sasisekaran et al., 2010). Our findings linking motor coordination to measures of both vocabulary and grammar, even phonology, support the domain-general view that these aspects of development, may not be distinct at all but rather associated with one another and might possibly show similar rates of development. While we were unable to fully replicate our findings using other (nontraditional) measures to assess coordination our research findings show that motor coordination and children's verbal abilities seem to be, in fact, two areas of development that are highly intertwined.

Our findings offer further support for the view that motor and language development are not separate abilities and may share a common and underlying mechanism (Diamond, 2000; Iverson, 2010). Understanding the true relationship between these two critical developmental areas is important in shedding light on early interventions targeted at helping children who show delays in language and/or motor skill difficulties. Our findings offer further support for the single-route view that language is fundamentally intertwined and there does not seem to be a dichotomy between the acquisition of rule-based versus word-based aspects of language.
What about Nonverbal Skills?

Our data seem to offer robust support for associations between motor and language abilities. This led us to question whether motor coordination is not only important in children's verbal development but also important in nonverbal abilities. For this reason, we evaluated relationships between our different measures of motor coordination and a measure of nonverbal intelligence. We found that motor coordination (measured only using the pegboard task) was associated with nonverbal intelligence. This was in line with literature linking overall cognitive abilities in children to motor skills (Diamond, 2000; Davis et al., 2011; Roebers & Kauer, 2009; Roebers et al., 2014), but not in line with research by Jenni et al. (2013) suggesting that motor skills and intelligence seem to be two distinct developmental areas. It is noteworthy that our findings were not supported when we used alternative assessments of motor skill. This nonsignificant finding in our alternate motor measure might show that this simple task is more sensitive at detecting individual differences in vocabulary and grammar but not cognitive measures. The pegboard task, might be a more ideal measure of motor coordination. Thus, using this common measure of fine motor coordination (the pegboard task) our data offer support for a more domain-general approach in children's abilities, since our findings show that the children who struggled with the pegboard task were also the children who struggled with not only language, but also nonverbal intelligence. These findings speak to the need for more research to examine children's motor and cognitive development as related areas of child learning, as opposed to separate fields of inquiry.
Problems with the Sequencing Task?

In this study, we attempted to link performance on the SRT task (as a measure of sequence learning) with language and cognitive measures. As is typically done in the literature we computed learning by calculating a rebound score for each child. This score was computed by subtracting children's performance on the final sequenced block from their performance on the random block (Lum et al., 2014). Our findings were consistent: using the traditional measure to assess learning, sequence learning was not associated with any measure of language or cognitive ability. This was not in line with any of the hypotheses we had posed, but did not completely diverge from other individual differences research adopting this task (Kidd & Kirjavainen, 2011; Lum & Kidd 2012). In attempts to explain these peculiar findings, we hypothesized that this lack of significant relationships across language and intelligence levels might be because this commonly used task may not be ideal at detecting individual differences. In a recent study, Siegelman et al. (2016) discussed the weaknesses of currently employed tasks of sequence learning at detecting individual differences. The authors explained that those tasks have been designed to detect differences in group-level research but can be psychometrically weak and flawed in design. The authors argue that the currently available tasks of sequence learning often involve (1) a limited number of trials in the test phase, and (2) the test items following the sequenced trails are often of the same level of difficulty. Furthermore, in some of these tasks, participants tend to perform at chance level making the data full of noise. The issues with currently used tasks of sequence learning may lead to measurement error, in addition to low reliability and validity. More issues arise with these traditional tasks of sequence learning when moderately low correlations exist between these various tasks that are supposedly measuring the same underlying concept. In an individual differences study among college students, Siegelman
and Frost (2015) used a variety of sequence learning measures (including the SRT and speech stream tasks) and found small to nonsignificant correlations between the various tasks of sequence learning used \( (r = -0.25) \). These findings suggest that a main problem in the literature is the use of tasks that have been generally robust at detecting group-level effects but once the interest shifts into individual differences research, results seem moderate at best. Therefore, before concluding that a relationship between sequence learning and language abilities is nonexistent, follow-up research should examine the research questions that we have posed using novel tasks that have been designed as strong measures capable of detecting differences among individuals in the community who vary in terms of skills and abilities (see Siegelman et al., 2016).

**Evaluating Our Alternative Motor Measure**

The measures chosen in this study are commonly used assessments of our variables of interest. For instance, while there are multiple measures of sequence learning the SRT task has been widely used in research assessing sequence learning and has been evaluated in meta-analyses (see Lum et al., 2014). The Grooved Pegboard task is also a commonly used assessment of fine motor coordination and has been used among multiple populations (e.g., Autism: Dawson & Watling, 2000; Multiple Sclerosis: Gallus & Mathiowetz, 2003). This assessment (as a measure of motor coordination) proved to be strongly associated with all our measures of interest (vocabulary, grammar, phonology, and nonverbal intelligence). Since our SRT task was not ideal at predicting sequence learning but also required motor coordination, we decided to attempt to replicate our findings by extracting a "not-so-traditional" measure of motor coordination from the SRT task. In terms of preliminary analyses, our pegboard task was strongly correlated the SRT accuracy measure (on Block 1). Results from the accuracy analyses of Block 1 showed that
Block 1 accuracy was associated with grammar and vocabulary scores ability, but not phonology or nonverbal intelligence. This accuracy measure is a very simple task for children, but it seems to be that children who struggle with this easy task are also the children who struggle with vocabulary and grammar. Furthermore, if the rebound effect extracted from the SRT task is truly not ideal at detecting individual differences in various cognitive abilities, future research should assess alternative ways of extracting data from the SRT task to make it a more meaningful measure in individual differences research. Research should also look at ways of adapting this task to make it more sensitive at detecting differences in typically developing populations with various skills and abilities.

**Dual versus Single Routes to Language Development: Where Do Our Findings Stand?**

In attempts to find support for sequence learning in relation to language acquisition, this study tested the hypotheses that we learn words and rules in language differently. While we did find robust relationships between motor coordination and language suggesting that language and motor coordination are two interconnected areas of development, we were unable to offer support for dual-route theories that view the acquisition of grammar and vocabulary as separate mechanisms (Pinker, 1998; Ullman, 2004). While prominent research has supported the procedural and declarative memory systems as "hubs" for different types of memory (Squire & Zola, 1996), and given that research with language impaired children shows that these children show difficulties in procedural learning (Lum et al., 2014). In light of the language literature and in a typically developing sample of children with a range of abilities, our research was unable to offer support for such a dissociation in language functioning. We found that strong relationships were evident between measures of grammar, vocabulary, and phonology thus suggesting that various aspects of language development are highly intertwined and inseparable as a child.
develops and progresses. Our findings are in support for single-route approaches to language
development suggesting that children's development of different aspects of language tend to be
highly associated with one another (Bates & Goodman, 1997; Bates & Dick, 2002; Diamond,
2000; Iverson, 2010). Our findings are also in support of domain-general theories suggesting that
language and motor development are two interrelated aspects of development (Iverson, 2010).

**Implications, Limitations, and Future Directions**

The present study examined the role of various cognitive and motor measures in relation
to child language development. We also examined whether there is possible support for dualistic-
approaches to language acquisition. While this study offered insight into the nature of language
suggesting that motor coordination is a critical component that is associated with children's
language and cognitive abilities. We cannot make causal conclusions since we only evaluated
our research questions using correlational and regression analyses. Furthermore, since our
assessments and tasks were administered at the same time, we can only conclude that our
findings hold for one time-point. Additionally, the youngest children in our sample were six
years old, which is beyond the critical period of language development. Thus, this study looks at
children's language abilities, in order to be able to offer insights on the development of language
and motor skills in children, however to be able to make developmental conclusions, future
research should look adopt a longitudinal approach starting off from infancy and following the
children into their school years. Furthermore, in this study we conclude that our findings offer
support for single-route approaches to language development in support of Elizabeth Bates's
view that different aspects of language are not separate constructs (Bates & Goodman, 1997) as
evidenced by high correlations between measures of vocabulary and grammar among the
children. However, while this is true it is really difficult to be able to tease out the development
of vocabulary versus grammar in children as language is very much driven by the children's environment (e.g., maternal input) and typically children who are exposed to low levels of grammar are also the same children who are exposed to low levels of vocabulary.

Our findings do offer support for the importance of motor skill in relation to various aspects of language abilities. Such results reinforce the importance of psychomotor intervention among children displaying language delays, in addition to highlighting the importance of motor skill development in day-to-day school activities. Our findings also show that cognitive factors are also associated with motor development. Further research should assess the importance of psychomotor intervention among children showing reading difficulties. Future research should also assess whether measures of motor coordination can be used as clinical markers for SLI. Furthermore, because any sequencing task (novel or not) would require children to engage in some form of fine motor coordination, future research should examine and control for children's motor abilities when looking at relationships between sequence learning and various aspects of language and cognition.

While conducting the study and observing the children completing both the sequence learning and motor coordination tasks, we noticed that these tasks were easier for some children, whereas other kids found these relatively simple measures harder to complete. It would be valuable for future research to videotape children as they complete these motor measures in order to understand the behavioral aspects of how different children complete these tasks. Such observations might offer insight into the different strategies that children who struggle with motor and language abilities might be adopting when completing these tasks. For instance, future observational research could answer questions such as: are these children showing difficulties because of the way they approach the task? or is it harder for them to hold on to the pegs
properly? Is the children's performance on the task verbally mediated (i.e., do they talk or engage in private speech as they complete this task)? Could their attention have to do with how they are completing the tasks?

While we were unable to find relationships between sequence learning and language abilities, we believe that the task adopted might have contributed to these non-significant findings. Therefore, prior to completely dismissing the importance of sequence learning in language, research should examine individual differences between sequence learning and language acquisition using tasks that have been developed with individual difference research designs in mind and thus capable of detecting differences across a wide range of typically developing populations (see Siegelman & Frost, 2016).

Conclusion

In conclusion, this study sought to answer four research questions pertaining to the nature of language abilities in a community sample of school-aged children. In relation to sequence learning and language development, we were unable to offer support or any significant associations between our measure of sequence learning and any assessment of language. We did, however, find strong associations between motor coordination and measures of vocabulary, grammar, and phonology in children, in addition to a measure nonverbal intelligence. Our findings support the view that one’s performance on multiple aspects of language are associated with one another and offer support for single-route theories of language acquisition (Bates & Goodman, 1997). The associations that we found between motor coordination and language abilities suggest that these two critical aspects of children's development are in fact associated with one another. Our findings are in line with domain-general approaches to development, such as the theory of embodied cognition that discusses the profound impact on children’s cognitive
development as a result of their use of their bodies and motor skills as they explore the world around them (Iverson & Thelen, 1999). These relationships may be bidirectional in nature; thus looking at the causal relationship of motor skill on cognitive abilities is a critical next step. Finally, our findings not only help us in understanding the basic processes of language development, but can also be helpful for many populations with language and learning impairments and can inform speech pathologists and psychomotor therapists as they develop interventions for children with language and motor difficulties.
Appendix A
Parent/Guardian Questionnaire

A.

Child’s Name: __________________________ Age: __________

Date of Birth: _______________ Home Phone Number: ______________________

School: __________________________ Grade: __________

Mother’s Name: __________________________________________________________

Occupation: ____________________________________________________________

Highest Level of Education: Less than High School/GED______ High School/GED ______
Some College but No Degree ______ Associate’s Degree ______ Bachelor’s Degree ______
Master’s Degree ______ PhD ______ JD/MD ______ Prefer not to say ______

Father’s Name: __________________________________________________________

Occupation: ____________________________________________________________

Highest Level of Education: Less than High School/GED______ High School/GED ______
Some College but No Degree ______ Associate’s Degree ______ Bachelor’s Degree ______
Master’s Degree ______ PhD ______ JD/MD ______ Prefer not to say ______

Occupation: ____________________________________________________________

Race/Ethnicity (check as many as applicable)

☐ White/Caucasian
☐ Black/African American/Caribbean
☐ Hispanic/Latino/a
☐ Asian
☐ Middle Eastern
☐ Other: ______________________

B.

List as many different languages that are spoken at home (for example, English, French, Spanish, Patois, Arabic, etc.): __________________________

________________________________

What is your child’s primary language? ____________________________________________
What other languages does your child speak? _____________________________________________

Mother’s Primary Language: _________________________________________________________

Other languages the mother speaks fluently: ____________________________________________

Father’s Primary Language: _________________________________________________________

Other languages the father speaks fluently: ____________________________________________

Who are the people the child frequently interacts with (parents, siblings, grandparents, nanny, etc.)?

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Relationship</th>
<th>Language spoken</th>
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</tbody>
</table>

C.

Is your child’s speech difficult to understand? No _____ Yes _____

(If YES, please explain) _____________________________________________________________

Do you think your child exhibits a language delay? No _____ Yes _____

(If YES, please explain) _____________________________________________________________

(If YES, when did you first notice the language delay? ________________________________)

Is there any history of the following in the family (check all that apply):

- Speech/Language disorders ______
- Hearing impairments ______
- Learning disorders ______

(If YES, please explain) _____________________________________________________________

Has your child been evaluated by or worked with any of the following? (check all that apply):

- Ear Nose and Throat (ENT) Doctor ______
- Neurologist ______
- Psychologist ______
- Speech Language Pathologist ______
- Audiologist ______
- Reading Specialist ______
Occupational Therapist _______ Physical Therapist _______ Other_________________________

(If YES, please explain) ________________________________________________________________

Do you think your child hears well? No _____ Yes _____

(If NO, please explain) ________________________________________________________________

D.

Does your child exhibit any antisocial or socially inappropriate behaviors (for example, avoiding interactions, consistently playing alone, etc.)? No _____ Yes _____

(If YES, please explain) ________________________________________________________________

Does your child exhibit any repetitive behaviors or self-stimulating behaviors (for example, rocking or arm flapping, etc.) for no apparent reason? No _____ Yes _____

(If YES, please explain) ________________________________________________________________

Does your child maintain eye contact? No _____ Yes _____

(If NO, please explain) ________________________________________________________________

E.

Which hand does your child use most? Left hand ______ Right hand ______ Both equally ______

Does your child evidence any motoric difficulties (for example, writing, drawing, eating, dressing, etc.)? No _____ Yes _____

(If YES, please explain) ________________________________________________________________

Is there any information you would like to share with us to help us understand your child better?

____________________________________________________________________________________

____________________________________________________________________________________

____________________________________________________________________________________
Appendix B

Parental Demographic Information

*Parents’ demographic information. Frequencies reported (percentages in parentheses).*

<table>
<thead>
<tr>
<th>Highest Level of Education</th>
<th>Mothers</th>
<th>Fathers</th>
<th>Primary Language</th>
<th>Mothers</th>
<th>Fathers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than a High School Degree</td>
<td>3 (5.1%)</td>
<td>4 (6.8%)</td>
<td>English</td>
<td>44 (74.6%)</td>
<td>44 (74.6%)</td>
</tr>
<tr>
<td>High School or GED</td>
<td>6 (10.2%)</td>
<td>12 (20.3%)</td>
<td>Other</td>
<td>15 (25.4%)</td>
<td>12 (20.3%)</td>
</tr>
<tr>
<td>Associate’s Degree</td>
<td>5 (8.5%)</td>
<td>3 (5.1%)</td>
<td>NA</td>
<td>—</td>
<td>3 (5%)</td>
</tr>
<tr>
<td>Some College but no Degree</td>
<td>8 (13.6%)</td>
<td>3 (5.1%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor's Degree</td>
<td>16 (27.1%)</td>
<td>18 (30.5%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master's Degree</td>
<td>15 (25.4%)</td>
<td>12 (20.3%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD</td>
<td>5 (8.5%)</td>
<td>3 (5.1%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD/JD</td>
<td>0</td>
<td>1 (1.7%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefer not to say</td>
<td>1 (1.7%)</td>
<td>4 (6.8%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: Out of the 63 children in the study, 59 parents responded to the parental questionnaire.*
Appendix C

Parental Reports of Children's Language Abilities

*Frequencies reported (percentages in parentheses).*

<table>
<thead>
<tr>
<th></th>
<th>Speech difficult to understand</th>
<th>Language Delay</th>
<th>Hearing Difficulties</th>
<th>Motor Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>56 (94.0%)</td>
<td>55 (91.5%)</td>
<td>57 (96.6%)</td>
<td>31 (52.5%)</td>
</tr>
<tr>
<td>Yes</td>
<td>3 (5.1%)</td>
<td>5 (8.3%)</td>
<td>2 (3.4%)</td>
<td>24 (40.7%)</td>
</tr>
</tbody>
</table>
References


longitudinal study. *Child: Care, Health and Development, 40*(1), 77-84. doi:
10.1111/cch.12003


1. Perruchet and Pacton (2006) discuss how the fields of implicit and statistical (or sequence) learning have stemmed from different research traditions. The authors, however, discuss that these two fields are more similar than they are different. Perruchet and Pacton (2006) indicate that this divergent approach provides major challenges and limitations for future research and recommend combining these two theories for more robust research.