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IMPLICIT SEQUENCE LEARNING IN CHILDREN WITH DYSLEXIA WITH AND WITHOUT LANGUAGE IMPAIRMENT

by

EMILY RIGGALL

Under the Direction of Robin Morris, Ph.D.

ABSTRACT

Procedural learning abilities have been shown to be deficient in children who meet criteria for Developmental Dyslexia (DD) and those who meet criteria for Specific Language Impairment (SLI; Lum et al., 2010; Menghini et al., 2006). Further, grammatical understanding has been linked to implicit sequence learning abilities across SLI and typically developing children (Lum, 2012). The present study examined implicit sequence learning, measured by the Serial Reaction Time Task (SRTT), in children who met criteria for DD with or without SLI. Implicit sequence learning was modeled using multi-level growth models of initial reaction time and learning slope across the repeated sequences of the SRTT. We further examined the predictive contributions of grammatical understanding, vocabulary abilities, phonological awareness, and diagnostic groups on implicit learning performance on the SRTT. Results showed language abilities and diagnostic group did not relate strongly to rates of implicit learning.

INDEX WORDS: Serial reaction time, Procedural learning, Implicit sequence learning, Dyslexia, Specific language impairment, Procedural deficit hypothesis

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by

EMILY RIGGALL

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Arts

in the College of Arts and Sciences

Georgia State University

2017

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2017

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by

EMILY RIGGALL

Committee Chair: Robin Morris

Committee: Rose Sevcik

Lee Branum-Martin

Electronic Version Approved:

Office of Graduate Studies

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Georgia State University

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1 INTRODUCTION

Children who exhibit poor language and reading abilities, and who experience related academic struggles, are at increased risk for a number of lifelong negative outcomes. Two specific groups of such children, those who meet the diagnostic criteria for Developmental Dyslexia (DD) or for Specific Language Impairment (SLI), have been identified as having particularly poor educational and psychosocial outcomes (Bishop & Snowling, 2004; Rice & Brooks, 2004). DD is defined by unexpected difficulty with reading acquisition, particularly in terms of phonological decoding of words in children with normal intelligence, no sensory or neurological impairment, and conventional instruction in reading, while SLI is characterized by impaired or delayed development of language skills in the presence of normal intellectual and sensory functioning (APA, 2000; World Health Organization, 2004). Though they are categorically distinct disorders, DD and SLI frequently co-occur and are characterized by similar language deficits (Nicolson & Fawcett, 2007). Identifying shared cognitive impairments underlying these disorders may reveal effective targets for interventions that can address the linked language and reading development weaknesses in such children (Nicolson & Fawcett, 2007).

The Procedural Deficit Hypothesis (PDH), proposed by Ullman and Pierpont (2005), has gained substantial support in recent years by suggesting a core cognitive deficit that provides a potential framework for understanding the overlapping profiles of SLI and DD. The Ullman & Pierpont hypothesis describes the key functional and anatomical distinctions between the grammar and vocabulary components of the language system: grammar being primarily supported by procedural learning system, and vocabulary being mainly a function of the declarative learning system. The PDH posits that the shared language deficits of SLI and DD can be largely explained by their shared abnormalities in the related brain or neurocognitive networks that support the procedural learning and memory system. Specifically, they propose that deficits in implicit sequence learning, primarily supported by the procedural neurocognitive system, are related to deficits in grammatical understanding, and are defined as problems in the awareness of the structure, sequence, and patterns of words within sentences.

Recent evidence has largely supported the PDH model showing that procedural learning and memory systems are indeed a relative weakness among individuals who meet criteria for DD or for SLI (Lum, Conti-Ramsden, Page, & Ullman, 2012; Lum, Ullman, & Conti-Ramsden, 2013; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). However, studies investigating the proposed connection between procedural learning deficits and impaired grammatical understanding have produced mixed findings. Primarily focused on SLI and typically developing (TD) populations, results have both supported (Gabriel et al., 2013; Hedenius et al., 2011; Lum, Gelgic, & Conti-Ramsden, 2010) and challenged (Gabriel, Maillart, Guillaume, Stefaniak, & Meulemans, 2011; Gabriel & Meulemans, 2014) the hypothesized relation between implicit sequence learning deficits and impaired grammatical understanding (Gabriel, Stefaniak, Maillart, Schmitz, & Meulemans, 2012; Lum et al., 2012; Tomblin, Mainela-Arnold, & Zhang, 2007).

Fewer studies have investigated the corresponding relation between procedural learning and memory impairments and specific language deficits among individuals who meet criteria for DD. This limitation in the most recent research may be explained by the fact that impairment in grammatical understanding is traditionally considered a central characteristic of SLI (Bishop & Snowling, 2004; Snowling & Hayiou-Thomas, 2006), while a weakness in phonological awareness is often considered the hallmark of DD (Morris et al., 1998), which was not specifically identified as a component of the PDH model. Interestingly, aspects of both grammar and phonological awareness are thought to be learned implicitly via the procedural learning system (Aslin, Saffran, & Newport, 1998; Evans, Saffran, & Robe-torres, 2009; Plante, Gomez, & Gerken, 2002). So in theory, both groups may share a deficit in this core cognitive learning system. Why one of these diagnostic groups has primary grammatical deficits while the other has phonological deficits is unknown. This proposed association of implicit sequence learning deficits in both SLI and DD, and its linkage with their respective grammatical understanding and phonological awareness deficits, remains largely unexamined.

The present study investigated the possibility that a shared impairment in procedural learning, specifically in implicit sequence learning, may be manifested in different language-related outcomes across individuals in the diagnostic categories of SLI and DD. The study evaluated whether implicit sequence learning was related to both phonological awareness and to grammatical understanding. At the same time, because lexical abilities were not expected to be related to implicit sequence learning in children who meet criteria for DD or SLI, this study also explored this potential disassociation to further differentiate the specific components of languages and how they related differentially to the proposed core underlying deficits in these groups. By exploring the relations between implicit sequence learning and different components of language within these diagnostic groups, the aim was to develop a more nuanced understanding of how implicit sequence learning may support language and reading development, and perhaps suggest targets for implicit learning intervention (Thomas et al., 2004).

Multiple Memory Systems

It is widely acknowledged that humans' ability to learn, store, and retrieve information is supported by multiple learning and memory systems in the brain (Knowlton, Mangels, & Squire, 1996; Squire, 2004). These neural systems support learning and memory across all sensory and content domains, although their roles in various aspects of language development remain unclear and the focus of extensive research. Two broad categories of these neural systems, the declarative and the procedural learning and memory systems, have received special attention. These systems are primarily distinguished by the level of awareness an individual has when learning or retrieving information, and by the number of exposures required to learn information using each system. While these two learning and memory systems are theoretically distinct, they rarely function completely independently on any learning task (Cohen & Squire, 1980; Evans et al., 2009). Rather, the procedural and declarative systems play interacting roles in learning and memory. Thus, while certain tasks may primarily recruit one system over the other, typically both systems are utilized to some degree.

The **declarative system** is characterized by learning that requires explicit effort to encode, or learn, and remember information. The bias of the declarative learning and memory system over the procedural system is exemplified by learning to play the piano. During the early stages of learning, an individual must be actively aware of learning to interpret the notes on the page. Each piece of information, such as the symbol of a specific note, is learned after seeing the symbol over a number of repetitions. Retrieval of this information requires conscious effort by the piano student during the early stages of learning to play. In other words, in the declarative system: new memories are encoded using explicit awareness and effort to learn the symbol and key relationships with minimal exposures, and then this information is retrieved with similarly conscious awareness.

In contrast, the **procedural system** is characterized by gradual implicit learning over multiple exposures without conscious awareness or effortful attention (Squire, 2004). This system is responsible for the acquisition and retrieval of both new and established cognitive and motor skills, as well as aspects of rule learning (Knowlton et al., 1996; Nissen & Bullemer, 1987; Packard & Knowlton, 2002). The procedural system is commonly referred to as the "implicit memory system" because both the learning and the retrieval of procedural memories occur without conscious awareness. In other words, individuals are capable of learning and responding adaptively to repeating patterns and stimuli in their environments even while they are unaware of the learning and the retrieval of these patterns or memories. Therefore, in the example of learning to play the piano, the declarative system is largely responsible for early effortful learning, and the procedural system becomes the primary driver as the individual becomes more fluent with practice. Following many exposures to the note symbols, and largely without explicitly trying to read faster, the individual learns to automatically respond to and play the stimuli more efficiently. Thus, the procedural system encodes the relationships and patterns of information over multiple exposures, retrieves, and interprets the information with a similar lack of explicit awareness.

One particular subtype of procedural learning and memory, implicit sequence learning and memory, is easily demonstrated by the common experience of effortlessly learning the order of information like songs on an album (Knowlton et al., 1996). After listening to an album multiple times, a listener will begin to anticipate the sequence of songs without actively trying to learn the order. In this example of implicit sequence learning, the listener is not explicitly aware of trying to remember the order of the songs, but rather after many exposures she implicitly learns and can predict the next song in the sequence.

Implicit sequence learning is commonly measured using variations on Nissen and Bullemer's (1987) serial reaction time (SRT) paradigm (Clark, Lum, & Ullman, 2014; Lum, Conti-Ramsden, Morgan, & Ullman, 2013; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006). In this foundational study of the attentional requirements of learning and memory, a light appeared in one of four locations on a computer screen and subjects were asked to press one of four corresponding buttons positioned directly below the visual stimulus. In one group, subjects responded to a random sequence of locations of the light stimulus for 8 blocks of 100 trials per block. In the other group, subjects were unknowingly exposed to a particular 10 light-position sequence that repeated 10 times per block for all 8 blocks: a total of 80 repetitions of the sequence. The subjects' reaction times were recorded and analyzed as the primary measure of interest in this task.

In this original study, the mean of the median reaction times (RT) across sets of 10 trials were presented graphically for each block, illustrating RTs across the entire session (Nissen & Bullemer, 1987). In the random location condition, participants on average responded 32ms faster to the stimuli during the final block than they did during the first block. The authors contrasted this small change in RT with the 164ms average decrease observed in the repeating sequence condition. This significantly different change in RT suggested that, though the individuals in the repeating sequence condition were unaware of the pattern being presented to them, they implicitly learned to anticipate the locations in the sequence and therefore were able to respond more quickly to presented stimuli after multiple presentations. In other words, improvement in speed (RT) over the repeated presentations of a sequence was interpreted as a demonstration of implicit sequence learning. This finding set the stage for future studies of implicit sequence learning.

An important advancement that has been incorporated into recent SRT studies is the addition of randomized sequences within blocks of trials presented both before and after the sequenced trial blocks. Thus, unbeknownst to the participant, on some blocks of trials the stimulus follows a sequence and on others the location is random. An increase in RT on random trials relative to sequenced trials is thought to indicate implicit learning of the sequence (Nissen & Bullemer, 1987). This interpretation is explained by contrasting the ability to predict the learned sequence with the inability to anticipate the random locations. Additionally, by inserting a block of randomized trials prior to the onset of the sequence, researchers control for participant's motor learning and adjustment to the task demands (Robertson, 2007). Allowing for motor learning may be particularly important for children with language impairments who are likely to have delayed motor skill acquisition (Adi-Japha, Strulovich-Schwartz, & Julius, 2011; Gabriel et al., 2012). The randomized trials presented after the sequenced trials allow for more direct comparison of RTs between learned sequence trials and unexpectedly random location trials.

Another recent variation on the task uses probabilistic rather than deterministic sequences. While most studies have examined deterministic sequences (Gabriel et al., 2012; Hedenius et al., 2011; Lum & Kidd, 2012; Nissen & Bullemer, 1987; Tomblin et al., 2007), some have used probabilistic sequences (Gabriel et al., 2011; Gabriel & Meulemans, 2014). Deterministic sequences repeat an unchanging set of locations, while probabilistic sequences incorporate some degree of statistically predetermined irregularity in the learned sequence. For example, one study used an 8-item sequence in which the probable location within the sequence appeared with a probability of .9 and the improbable location appeared with a probability of .1 (Gabriel et al., 2011). Some have argued that probabilistic sequences are more representative of naturalistic grammatical structure (Aslin et al., 1998; Gabriel et al., 2011). Implicit sequence learning has been observed in SRT paradigms using both deterministic and probabilistic conditions.

Language and the Procedural System

Specific Language Impairment (SLI) is defined by delayed or impaired language skills despite normal functioning in other domains. The PDH suggests that the characteristic language deficits of SLI are language-specific outcomes resulting from brain abnormalities that underlie the broad procedural learning and memory system (Ullman & Pierpont, 2005). The influence of the procedural system has been demonstrated across visual (Lum et al., 2012) and auditory modalities (Evans et al., 2009; Gabriel & Meulemans, 2014). Studies that have addressed the PDH have also reported that procedural learning is impaired in children who meet criteria for SLI across multiple content domains, including motor sequence learning (Gabriel et al., 2013; Lum et al., 2012; Tomblin et al., 2007), verbal learning (Evans et al., 2009), and category learning (Kemeny & Lukacs, 2010a). Thus, while modality likely has an effect on learning capacity (Conway & Christiansen, 2005), recent research has demonstrated that implicit visual sequence learning is related to implicit auditory sequence learning in both TD and SLI children (Gabriel & Meulemans, 2014). Given the association among procedural learning abilities across modalities, the connection between the procedural system and language abilities can appropriately be assessed using SRT tasks utilizing different modalities of presentation.

Multiple Memory Systems and Language Components

Procedural Learning and Grammar. The PDH further suggests that there is a dissociation between grammar and vocabulary abilities within the language system and that these two components are supported by two functionally and anatomically distinct learning and memory systems. Ullman & Pierpont (2005) proposed that grammar is primarily supported by procedural learning, while vocabulary is mainly supported by declarative learning. This link between procedural learning and grammar abilities though remains controversial, with findings both supporting (Evans et al., 2009; Gabriel et al., 2013; Hedenius et al., 2011; Lum et al., 2012;

Tomblin et al., 2007) and challenging (Gabriel et al., 2012; Kelly, Griffiths, & Frith, 2002; Lum & Bleses, 2012) the hypothesis.

In a landmark study supporting the hypothesized role of implicit learning in grammar understanding, Tomblin (2007) measured SLI and TD children's implicit sequence learning ability as well as their semantic and grammatical language abilities. Subjects were then categorized by higher or lower grammatical understanding, by higher or lower vocabulary understanding, and finally, by diagnostic category. Procedural learning in this study was evaluated using a version of the classic visuospatial SRT task, which used a 10-item deterministic sequence. The study utilized growth curve analysis to observe the rate and pattern of individuals' procedural learning across trials on the SRT task. They reported that individual differences in grammatical understanding were associated with implicit sequence learning growth curves. Importantly, this relation between individual grammatical ability and procedural learning growth curves closely resembled the relation between diagnostic category (i.e., SLI or TD).

Other studies have challenged this hypothesized relation between procedural system deficits and impaired grammar abilities (Gabriel et al., 2011; Gabriel & Meulemans, 2014; Hedenius et al., 2011; Lum & Bleses, 2012). One study found, using an 8-item probabilistic sequence in a visuospatial SRT task, SLI and TD children did not differ significantly in terms of rate of sequence learning across the session, nor in the differences in RT between the final repetition of the sequence and the final block of randomized trials (Gabriel et al., 2011). In a similar SRT study that used a 10-item deterministic sequence, Lum and Bleses (2012) reported no significant difference between SLI and TD children's RTs on sequence trials compared with randomized trials.

The growing body of evidence from SLI and TD children investigating the hypothesis that grammatical understanding is associated with implicit sequence learning presents an interesting parallel to studies of procedural learning abilities in children and adults with DD (Kelly et al., 2002; Lum, Ullman, & Conti-Ramsden, 2013b; Roodenrys & Dunn, 2008; Rüsseler, Gerth, & Münte, 2006). In line with PDH, Nicolson & Fawcett (2007; 2011) suggested a deficit in automatizing skill learning also could explain the core language impairments found in DD. Implicit sequence learning deficits have been reported in DD just as they have in SLI (Menghini et al., 2006; Vicari et al., 2003), but the relationship between implicit sequence learning and grammatical understanding in DD has not been investigated.

Deficits in the ability to analyze components of words, or phonemes, is often considered a hallmark of DD (Morris et al., 1998). This ability, known as phonological awareness, is defined as the knowledge and understanding of phonemes, the distinct units of sound that are combined in particular patterns to form words. Children who struggle to learn phonemic patterns, and likely to meet criteria for DD, are also likely to have difficulty mastering the larger patterns underlying grammar development in language, often resulting in an SLI diagnosis. This is consistent with the reported co-occurrence of DD and SLI that is widely observed among these clinical populations (Stark & Tallal, 1988). Recently, over 70% of poor readers in a second grade sample were found to have a history of language deficits in Kindergarten (Catts, Fey, Zhang, & Tomblin, 2009). Scarborough (1998) also found that the best predictors of eighth grade reading performance in children with reading disabilities were their cognitive-linguistic abilities, including phonological awareness, in second grade. Longitudinal studies have shown that 25% of children identified with SLI in Kindergarten meet criteria for DD in second, fourth, and eighth grades. Similarly, 20% of children identified with DD in upper grades met criteria for

SLI in Kindergarten (Catts, Adlof, Hogan, & Weismer, 2005; Sawyer, 2006). In other words, although a relative weakness in phonological awareness is most commonly considered central to DD, difficulties with phonological skills have also been observed in SLI (Bishop & Snowling, 2004). Similarly, while a relative weakness is grammatical understanding is most commonly considered central to SLI, difficulties with grammar have been observed in DD (Muter, Hulme, Snowling, & Stevenson, 2004). Taken together, these findings suggest that DD and SLI likely share underlying cognitive and related language impairments that may result from shared difficulties with implicit learning (Nicolson & Fawcett, 2007; Vicari et al., 2003).

Vocabulary & Declarative System. Vocabulary ability, defined as understanding the meaning of words, is typically associated with the more effortful and rapid declarative learning system (Ullman & Pierpont, 2005). Several recent studies have supported this relationship between declarative learning and vocabulary skills among TD and SLI children. Lum and colleagues (Lum et al., 2012) demonstrated that among TD children and those with SLI, lexical ability, as measured by the Expressive One-Word Picture Vocabulary Test and the Receptive One-Word Picture Vocabulary Test, was significantly correlated with declarative learning ability, as measured by the declarative memory subscale of the Children's Memory Scale, but not with procedural learning, as measured by a version of the serial reaction time (SRT) task. In separate study, Lum and Kidd (2012) observed that in a sample of TD children, declarative memory, as measured by the Word Pairs subtest from the Children's Memory Scale, was significantly correlated with vocabulary, as measured by the British Picture Vocabulary Scale-2nd, but not correlated with grammatical ability, as measured by a past tense task (Marchman, Wulfeck, & Ellis Weismer, 1999). These findings of the association between declarative memory and vocabulary are underscored by observations that when SLI and TD children were grouped based on their vocabulary abilities, rather than their diagnostic categories, there were no differences between the groups on procedural learning abilities (Hedenius et al., 2011; Tomblin et al., 2007). Despite different methods of assessing vocabulary, procedural memory, and declarative memory, converging evidence indicates that, at least among TD individuals and those with SLI, vocabulary is primarily associated with the declarative learning and memory system and less with the procedural learning and memory system.

Interestingly, the learning system supporting phonological awareness, a key component of DD, remains unexamined. While the declarative and procedural learning and memory systems rarely function independently on any learning task, it is likely that phonological awareness preferentially recruits one system or the other (Cohen & Squire, 1980; Evans et al., 2009). Children must be taught explicitly to translate or map phonemes onto orthographic representations in order to learn to read. However, words can also be conceptualized as a series of phonemic patterns (in much the same way that grammar consists of a structure or pattern of words) that individuals may learn implicitly from their environment. Phonological awareness is also typically measured by the ability to analyze the sound components within words, similar to the way in which grammatical understanding is measured by the ability to analyze words within sentence structures. Thus, it remains unclear whether phonological awareness is supported primarily by the declarative or by the procedural system, or perhaps represents an ability that requires more interfacing between systems, which may be a key to its impaired development in some children.

1.1 Purpose of the Study

While previous studies have examined the PDH and related hypotheses in the context of pure SLI or pure DD, examination of a clinically complex sample of individuals may further expand our understanding of the association of implicit sequence learning with grammatical understanding, and the lack of association with vocabulary abilities. The present study applied a visuospatial implicit sequence learning and memory measure (SRT task) to a co-morbid sample that includes children who meet criteria for DD only, and those who meet criteria for both DD and SLI (DD+SLI). This study extended the previous research to investigate whether a deficit in implicit sequence learning underlies similar language outcomes in children with DD and DD+SLI. This complex sample also enabled the investigation of the possible link between procedural learning and phonological awareness. Growth curve analyses were used to explore the relations of implicit sequence learning with vocabulary and grammar abilities in this highly co-morbid sample. In addition these analyses were used to investigate whether phonological awareness, the hallmark of DD, is also related, or not, to implicit sequence learning.

1.2 Hypotheses

Aim 1. To evaluate the PD hypothesis that there is a relation between implicit sequence learning ability and grammatical understanding, but not vocabulary ability, in children with DD and DD+SLI.

Hypothesis: Based on research demonstrating a significant correlation between implicit sequence learning and grammatical understanding in SLI, as well as the demonstrated deficit in implicit sequence learning in both SLI and DD, it was predicted that implicit sequence learning is related to grammar abilities, but not to vocabulary, among children with DD and those with both DD+SLI.

Aim 2: To investigate the relation between implicit sequence learning and phonological awareness in children with DD and DD+SLI.

Hypothesis: Phonemic patterns within words are conceptually learned in much the same way that grammar patterns within sentences are learned and supported by the procedural system. Due to the theoretical similarity between phonological pattern awareness and grammatical structure awareness, it was predicted phonological awareness is likely impaired in DD and DD+SLI as a result of their shared impaired procedural learning system. Thus, it was expected that the relation between implicit sequence learning and phonological awareness would be more similar to the relation between implicit sequence learning and grammar rather than to the relation between implicit sequence learning and vocabulary.

Alternative Hypothesis: Alternatively, if phonological awareness were primarily supported by the declarative system, it would be expected that the relation between implicit sequence learning and phonological awareness would more closely resemble the relation between implicit sequence learning and vocabulary abilities.

Aim 3: To investigate differential implicit sequence learning abilities between children with DD and children with DD+SLI.

Hypothesis: Implicit sequence learning has recently been studied broadly among individuals who meet criteria for SLI or for DD. However, this type of learning has never been evaluated among children who meet criteria for co-morbid DD and SLI. Evidence that both diagnostic groups demonstrate implicit sequence learning impairments along with the theoretical hypothesis that procedural learning underlies the primary deficits that characterize DD and SLI suggests that implicit sequence learning deficits will be observed in both DD only and DD+SLI groups. Given their more global clinical impairments, it is predicted that children who meet criteria for co-morbid DD+SLI will demonstrate greater implicit sequence learning deficits than children who meet criteria for DD only.

2 METHODS

2.1 Participants

73 children aged 8-15 years (M=10.3 years, SD=1.9) were recruited from public elementary and middle schools in Atlanta, GA. Subjects in all groups were recruited as part of an intervention study focused on children with dyslexia/reading disabilities. Subjects were referred for the study by their teachers/schools based on their struggles in learning to read and poor school-performed standardized reading assessments. Children in regular or special education were invited to participate based on these referrals. All subjects were required to be native speakers of English and to meet explicit study assessment criteria based on independent testing by study evaluators. All subjects had at least average intellectual functioning (SS≥80) on at least one subscale of the Wechsler Abbreviated Scale of Intelligence (WASI-II; Wechsler, 2011). Children with chronic absenteeism (>15 absences per year), hearing impairment (<20/40), serious emotional/psychiatric disturbance, chronic medical/neurological condition (e.g., seizure disorder) were excluded.

2.1.1 *Developmental Dyslexia*

Children met study criteria for DD if they met Low Achievement criteria defined as a score ≥ 1SD below age-norm expectations (SS≤85) on any of the following: Woodcock Johnson (WJ-3) Broad Reading Cluster subtests or the composite, (Letter-Word Identification, Reading Fluency, Passage Comprehension; Woodcock, McGrew, & Mather, 2001)); the Basic Reading Cluster subtests or composite (Letter-Word Identification and Word Attack); or subtests on the Test of Word Reading Efficiency (TOWRE-2).

2.1.2 Specific Language Impairment

Children met study criteria for SLI if they met Tomblin SLI criteria (1996): scored ≥ 1SD below age-norm expectations (SS≤85) on at least two of following measures: the Core Language Composite of the Clinical Evaluation of Language Fundamentals (CELF-4), Peabody Picture Vocabulary Test (PPVT-4), and Test of Narrative Language (TNL).

2.2 Measures

The *Wechsler Abbreviated Scale of Intelligence, Second Edition* (WASI-II; Wechsler, 2011) served as the measure of general verbal and non-verbal cognitive abilities, as well as a proxy for IQ. In the present study, low WASI-II scores were used as exclusionary criteria for all subjects. This widely used measure has been demonstrated to have high reliability and validity and has been normed on a school-aged population.

Four subtests of the *Woodcock Johnson, Third Edition* (WJ-III; Woodcock et al., 2001) were used to index reading skill. Focusing on specific facets of reading, the non-timed Letter-Word Identification, Passage Comprehension, and Word Attack subtests, as well as the timed Reading Fluency subtest were administered. Each of these subtests has been shown to have high reliability and validity and is normed in a representative school-aged population (Schrank, McGrew, & Woodcock, 2001)

The *Test of Word Reading Efficiency, Second Edition* (TOWRE-2; Torgeson, Wagner, & Rashotte, 2011) was used to test the timed reading of real English words (Sight Word Efficiency) and of pseudowords (Phonemic Decoding Efficiency). On both subtests, the items are ordered from easiest to most difficult, and the examinee reads as many items as possible in 45 seconds. The TOWRE is a normed and highly reliable and valid measure of speeded reading (Hayward, Stewart, Phillips, Norris, & Lovell, 2008).

Three subtests from the *Comprehensive Tests of Phonological Processing, Second Edition* (CTOPP-2; Wagner, Torgesen, Rashotte, & Pearson, 1999) were used to measure phonological awareness. The three subtests, *Elision*, *Blending*, and *Phoneme Isolation*, form a composite score for phonological awareness, which measures a child's awareness of and access to the phonological structure of oral language. The CTOPP-2 has shown robust validity and reliability statistics (Wagner et al., 1999).

Subtests from the *Clinical Evaluation of Language Fundamentals, Fourth Edition* (CELF-4; Semel, Wiig, & Secord, 2003) were used to obtain a measure of general language ability (subtest used varied depending on the age of the child): Concepts and Following Directions, Word Structure, Recalling Sentences, Formulated Sentences, Word Classes 1 & 2, and Word Definitions. The Sentence Assembly subtest was also given to assess a child's ability to generate grammatically correct and semantically meaningful sentences. The CELF-4 has been shown to have high reliability and validity and has been normed using a representative school-aged sample.

The *Peabody Picture Vocabulary Test, Fourth Edition* (PPVT-4; Dunn & Dunn, 2007) was used to measure lexical/vocabulary skills. The PPVT-4 is a well-established measure of receptive vocabulary and has been shown to have good reliability and validity.

The *Test of Narrative Language* (TNL; Gillam & Pearson, 2004) was administered to measure how well children use language in functional discourse. Three formats are used: no picture cues, sequence picture cues, and single picture cues. The present study used the maximum available age-based norms (12 years of age) as the norm for older children in this study. Using this conservative approach, standard scores were obtained for narrative comprehension, oral narration, and for overall performance (Index of Narrative Language

Ability). High sensitivity (.92) and specificity values (.87) argue for its use as a test for the identification of language impairments in children ages 5-11+.

Three composite language component scores were calculated to ensure language variables appropriately incorporated both expressive and receptive abilities in each of three domains: vocabulary, grammar, and phonological understanding. The standard scores from the PPVT-4 and WASI-II Vocabulary subtest were averaged to create a vocabulary composite score that represents both receptive and expressive lexical abilities. Similarly, individuals' scores from the CELF-4 Repeating Sentences and Formulated Sentences subtests were averaged to create a grammar composite score that captured both receptive and expressive grammatical abilities. Finally, the phonological awareness subscale of the CTOPP-2, a composite of the Elision, Blending and Phoneme Isolation subtests, was used as a measure of phonological understanding.

The *Serial Reaction Time* (SRT) task is a commonly used computerized measure of implicit sequence learning (e.g., Lum, Kidd, Davis, & Conti-Ramsden, 2010). In this study, the subjects were presented with six blocks of items, each with 60 items (see Figure 1). Subjects were asked to press a button on a keypad that corresponded to the location of a smiley face in one of four positions on a computer screen (see Figure 2). Unknown to the participants, the smiley face appeared in random locations throughout the first block of items. In the second, third, fourth, and fifth blocks, the smiley face appeared in a repeated *deterministic sequence of 10 locations* (repeated sequence). In the sixth and final block, the location of the smiley face was again random. Therefore, the subjects were given blocks of items (6 blocks of 60 trials) in which the location of the stimuli were: random, sequenced, sequenced, sequenced, sequenced, random.

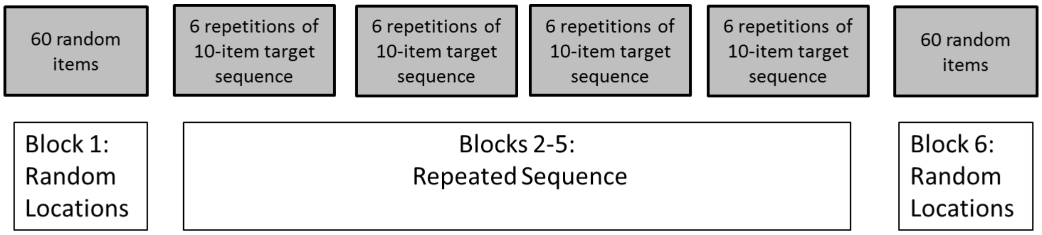

Figure 1. Structure of SRT Task.
Blocks 1 and 6 are composed of 60 items in random locations. Blocks 2-5 each include 6 repetitions of a 10-item deterministic sequence.

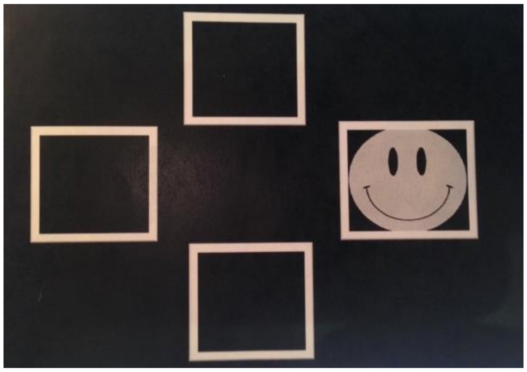

Figure 2. Display on the computer screen in the present SRT task.

While the SRT task has been a widely used measure of implicit sequence learning, the structure of this task is far from standardized across studies. Differences in the SRT task design (i.e., using deterministic versus probabilistic target sequences) and methods for analyzing SRT data vary substantially. It is possible that these methodological differences may explain the discrepant results regarding the level of association between implicit sequence learning and grammatical understanding within SLI and TD populations. The following task components have been altered across studies:

Variation in number of sequence repetitions. The number of sequence repetitions is a particularly overt example of such inconsistency across studies (Lum, Ullman, & Conti-Ramsden, 2013b). In recent studies, the number of exposures to the repeated sequence within the SRT task has varied widely from as many as 96 repetitions of the sequence (Gabriel et al., 2011), 72 repetitions (Lum et al., 2010), 54 repetitions (Lum et al., 2012), 48 repetitions (Gabriel et al., 2013), to as few as 24 repetitions of the sequence (Lum et al., 2010; Lum & Kidd, 2012). Predictably, the number of repetitions of the target sequence significantly affects the information learned, particularly by individuals who meet clinical criteria. As Lum et al. (2013) demonstrated, fewer exposures to the repeated target sequence predicted larger differences between participants who met criteria for SLI and their age-matched controls. In other words, individuals with SLI may be able to achieve the same degree of implicit learning as typically developing children with more exposures to information. The SRT paradigm used in *the present study exposed the participants to 24 repetitions of the target 10-item sequence (6 repetitions of the target sequence within each of 4 blocks).*

Variation in length of target sequence. Another methodological difference within the SRT literature is inconsistency in the number of items in the target sequence. Recent SRT studies have used repeated target sequences that vary from 8 items (Gabriel et al., 2011), 9 items (Menghini et al., 2006), 10 items (Lum et al., 2010; Nissen & Bullemer, 1987; Tomblin et al., 2007) to 12 items in length (Gabriel et al., 2013). It is unclear what effect differing sequence lengths may have on participant learning, however it is likely that learning a longer repeated sequence may be an inherently more difficult task than learning shorter sequence. *The present study used 10-items in the repeated target sequence*, the most common length.

Variation in sequence type. Most studies have examined deterministic sequences (Gabriel et al., 2012; Hedenius et al., 2011; Lum et al., 2012; Nissen & Bullemer, 1987; Tomblin et al., 2007), although some have used probabilistic sequences (Gabriel et al., 2013, 2011; Kemeny & Lukacs, 2010b). While some have argued that a probabilistic sequence is more representative of naturalistic grammatical structure, the deterministic sequence allows for more controlled examination of implicit sequence learning across the session and among individuals. Additionally, evidence has demonstrated that implicit sequence learning occurs using both deterministic and probabilistic sequences (Gabriel et al., 2013; Lum et al., 2012). *The present study used a deterministic sequence* (if the topmost location is 1, the right position is 2, the bottom location is 3, and the left position is 4, the sequence used followed the original sequence used by Nissen & Bullemer (1987): (4,2,3,1,3,2,4,3,2,1).

In sum, in the current study subjects were exposed to 24 repetitions of a 10-item deterministic sequence (60 random items, followed by 24 repetitions of the target 10-item sequence, ending with 60 random items).

2.3 Data Analyses

The method of analysis in this study aims to maximize the generalizability of findings beyond RT difference scores between the random trial blocks and the sequenced trial blocks, which are frequently reported. Previous studies employing RT difference scores (between sequenced and random blocks) have eliminated opportunities to evaluate more subtle differences among group's and individual's learning, which may also be related to variations in study design. The individual growth curve analysis in this study was designed to capture the nuanced learning trends in the SRT task.

Reaction time aggregation. There are different approaches to analyzing SRT data across studies. For example, one recent SRT study evaluated the mean of the median RTs obtained in each of seven blocks (Menghini et al., 2006). Other studies used the median RT of each individual within each block (Gabriel et al., 2011; Lum et al., 2010). Another study calculated median RT across successive sets of twenty correct trials, regardless of block, and eliminated incorrect trial responses (Tomblin et al., 2007). Lum and Kidd (2012) converted all RTs to z-scores, to control for within subject variability in motor speed (Thomas et al., 2004) and eliminated any scores that were more than three standard deviations above or below the individual participant's mean RT (to control for anticipation responses and attention lapses). These discrepant approaches to aggregating RT data, in particular using individual's z-scores, make it difficult to compare results across studies since the differences in study design may be confounded by aggregation methods. *The present study used an individual's median reaction time value calculated across only correct responses within each 10-item span (10 random locations items in the random blocks or the 10-item sequence in the repetition blocks). Additionally, RTs on individual items that exceed 3 standard deviations from each individual's mean RT across all items (random and sequenced) were eliminated as outliers.*

Analysis. Most studies approach the analysis of aggregated RT with traditional difference scores between random and repetition blocks (e.g., Lum et al., 2012; Nissen & Bullemer, 1987). ANOVA is a common method of evaluating difference scores in RT across the SRT task. In one recent study, Gabriel (2011) used a 2x2 ANOVA and a 12x2 ANOVA to evaluate the differences among blocks. In contrast to difference scores and the ANOVA approaches, growth curve analyses have also been used to explore more nuanced learning trends across the SRT task in SLI and TD populations (Tomblin et al., 2007). *The present study aimed to maximize generalizability by using an individual growth curve analyses approach in order to more fully describe learning throughout the task.*

3 RESULTS

3.1 Participant characteristics

Table 1 contains descriptive characteristics of the participants in this study. The table presents the mean and standard deviation for the participants' age, and composite vocabulary, phonological awareness, and grammar scores. Accuracy on the full SRT task was calculated as a percent correct and is consistent with levels described in similar studies (e.g., Lum, 2010). Table 2 presents the correlations among the language variable scores and the diagnostic status of participants.

Table 1. Participant characteristics.
Descriptive statistics of the participants' age and language scores across the full sample, among children who meet criteria for DD only and those who meet criteria for co-morbid DD+SLI.

Characteristics	All *M (SD)*	DD only *M (SD)*	DD+SLI *M (SD)*
Age	10.27 (1.85)	10.08 (1.76)	10.78 (2.05)
WJ-III LW Standard Score	87.53 (10.88)	88.96 (9.22)	83.75 (13.96)
WJ-III WA Standard Score	88.40 (10.34)	90.43 (8.08)	83.00 (13.58)
TOWRE-2 SWE Standard Score	76.63 (10.49)	77.47 (10.16)	74.40 (11.31)
TOWRE-2 PDE Standard Score	75.12 (10.15)	75.87 (8.79)	73.15 (13.16)
WASI-2 FSIQ Standard Score	94.26 (11.50)	97.83 (10.87)	84.80 (6.94)
Vocabulary Standard Score	96.54 (12.52)	101.18 (11.19)	84.34 (5.54)
Phonological Awareness Standard Score	81.62 (11.42)	83.94 (10.79)	75.45 (10.95)
Grammar Scaled Score	7.89 (2.65)	8.53 (2.63)	6.20 (1.90)

Note: DD=Developmental Dyslexia; DD+SLI=co-morbid Developmental Dyslexia and Specific Language Impairment; SD=standard deviation; WJ-III LW=Woodcock Johnson, Third Edition Letter Word Identification; WJ-III WA=Woodcock Johnson, Third Edition Word Attack; TOWRE-2 SWE=Test of Word Reading Efficiency, Second Edition Sight Word Efficiency; TOWRE-2 PDE= Test of Word Reading Efficiency, Second Edition Pseudoword Decoding Efficiency; WASI-2 FSIQ= Wechsler Abbreviated Scale of Intelligence, Second Edition Full Scale Intelligence Quotient; Vocabulary Score= average of standard scores (age-normed average standard score=100, std=15) from PPVT-4 and WASI Vocabulary; Phonological Awareness Score=standard score for phonological awareness subscale on CTOPP-2; Grammar Score=average of scaled scores (age-normed average scaled score=10, std-3) from the Recalling Sentences and Formulated Sentences on CELF-4.

Table 2. Language variable correlations.
Correlations among vocabulary, phonological awareness, grammar scores, and SLI diagnosis.

Characteristics	1.	2.	3.	4.
1. Vocabulary Score	1.00			
2. Phonological Awareness Score	0.42*	1.00		
3. Grammar Score	0.60*	0.44*	1.00	
4. Diagnosis	-0.60*	-0.34*	-0.39*	1.00

Note: *= p<.0001; Vocabulary Score= average of standard scores from PPVT-4 and WASI Vocabulary; Phonological Awareness Score=standard score for phonological awareness subscale on CTOPP-2; Grammar Score=average of scaled scores from the Recalling Sentences and Formulated Sentences on CELF-4; Diagnosis=DD+SLI (1) or DD only (0) diagnosis.

3.2 Examining learning trajectories

Individual performance trajectories, using median RT for each repetition block across the sequenced trials, were examined using loess plots (Figure 3). Individuals' learning trajectories were then plotted using linear regression to estimate individual growth (Figure 4). These linear trends were visually inspected and compared to the loess plots of all participants' performance across the sequenced trials. Given the relative similarity between the loess and linear representations of all individuals' performance, it was determined that change in RT across the repetitions of the target sequence blocks would be most appropriately represented using a linear slope across all subsequent models.

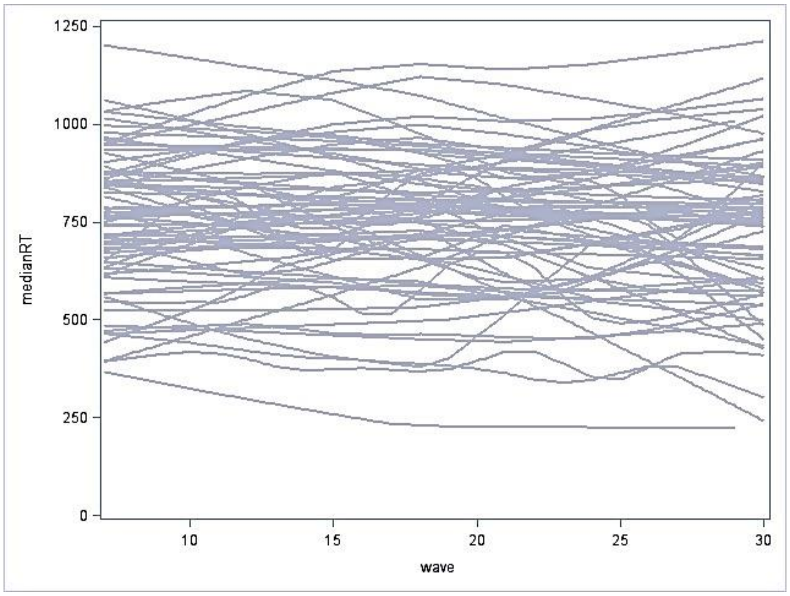

Figure 3. Local polynomial regression (loess) of performance trajectories.
This figure illustrates loess estimations of all participants' median RTs across each target sequence repetition.

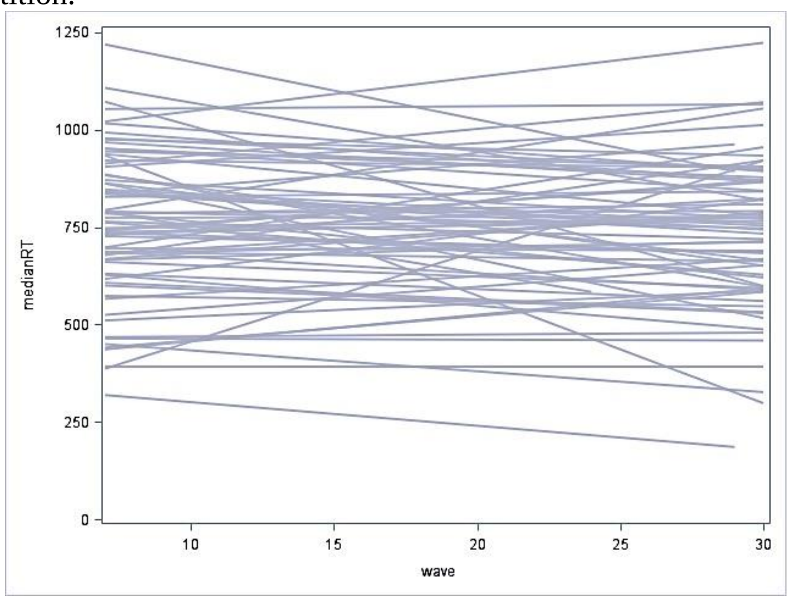

Figure 4. Linear regression of performance trajectories.
This figure illustrates linear regression estimates of each participants' median RTs across each target sequence repetition.

3.3 Modeling implicit sequence learning

Implicit sequence learning across the 24 repetitions of the target sequence was modeled using individual linear growth curves (i.e., a multilevel model of time within student; see Singer, 1998). Six distinct models of performance across the 24 repetitions of the target sequences were fit using maximum likelihood estimation to evaluate individual initial RT (median RT across the first of the 24 repetitions of the target sequence), individual learning slope, and the predictive contribution of vocabulary ability, grammatical understanding, phonological awareness, and co-morbid SLI diagnosis to initial RT and slope. The models that were fit are shown in Table 3.

Table 3. Equations for Models 1-6

Model 1: RT = intercept
Model 2: RT = intercept – slope(rep)
Model 3: RT = intercept – slope(rep) + estimate(vocab) + estimate(slope*vocab)
Model 4: RT = intercept – slope(rep) + estimate(gram) + estimate(slope*gram)
Model 5: RT = intercept – slope(rep) + estimate(PA) + estimate(slope*PA)
Model 6: RT = intercept – slope(rep) + estimate(SLI) + estimate (slope*SLI)

Note. rep = number of target sequence repetition (i.e., observation 1-24); vocab= vocabulary composite score; gram= grammar composite score; PA=phonological awareness composite score; SLI=with or without a co-morbid diagnosis of SLI

Results from these six models are reported in Table 4. In Table 4, each model has two columns: one for the regression estimates and one for the associated standard errors. Fixed effects are presented in the top portion of the table while the random effects, including a chi-square test of the random effect, and the residual variance, as well as the associated log likelihood for each model are presented in the bottom portion.

Overall, the results of the models that included linear growth and different language or diagnostic characteristics did not differ. In particular, the learning slopes across Models 2-6 were consistent and not statistically significant. Models 3-5 resulted in language characteristic estimates that were consistent across models and are therefore described together.

Table 4. Models analyzing predictors of implicit sequence learning characteristics

	1. Intercept only		2. Intercept & Slope		3. Intercept, Slope, Voc, Interaction		4. Intercept, Slope, Gram, Interaction		5. Intercept, Slope, PA, Interaction		6. Intercept, Slope, Diagnosis, Interaction	
Fixed Effects	est.	SE	est.	SE	est.	SE	est.	SE	est.	SE	est.	SE
Intercept	747.24	19.29	770.47	24.96	770.59	24.48	770.31	24.91	770.47	24.88	780.08	29.20
Slope			-1.28	0.87	-1.28	0.87	-1.27	0.85	-1.28	0.86	-0.95	1.02
Lang. Variable					3.32	1.96	4.65	9.45	-1.50	2.19	-35.12	55.83
Slope*Lang.					0.03	0.07	0.56	0.32	0.07	0.08	-1.22	1.94
Random Effects												
Intercept Var.	26153		37766		36059		37598		37496		37524	
Slope Var.			35.24		35.07		32.90		34.58		34.98	
Covariance			-636.18		-653.18		-652.21		-622.71		-645.13	
Residual	23944		22136		22136		22140		22135		22135	
Fit Statistics												
BIC	22425.5		22384.1		22385.7		22385.4		22391.7		22390.5	
-2LL	22412.6		22358.3		22351.4		22351.1		22357.4		22356.2	

Notes: est. = Estimate; SE = standard error; Voc= vocabulary; Gram= grammar; PA= phonological awareness; Diag= DD or DD+SLI diagnosis; Lang. Variable= language variable; Var.=variance -2LL = -2 log likelihood or deviance.

3.3.1 Model 1: Intercept only

This model is of stability (i.e., limited/no learning), indicating that the data can be represented using only an intercept estimate, without need for accounting for implicit sequence learning, which would be demonstrated by a reduction in RT across the 24 sequence repetitions (i.e., RT= 747.24 ms). Figure 5 illustrates the predicted outcomes of Model 1 across the 24 repetitions of the sequence. Further, Model 1 showed significant variability across participants, which is not reduced across subsequent models.

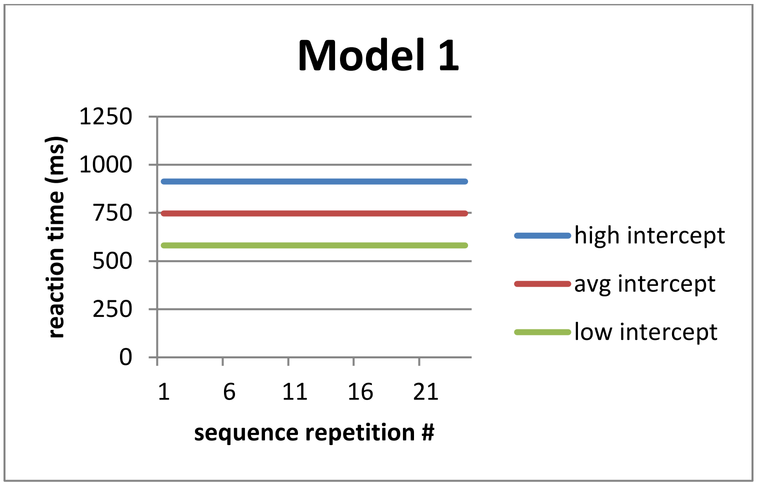

Figure 5. Model 1 predicted outcomes.
This figure illustrates the performance across the 24 repetitions of the target sequence predicted by this model for a participant with average initial RT, as well as participants with initial RTs one standard deviation above and below the average.

3.3.2 Model 2: Intercept & Linear Slope

Model 2 describes participants' initial RT and added participants' linear slope to estimate their changing performance across the 24 sequence repetitions (i.e., RT = 770.48 - 1.28(rep)). The intercept estimates the initial average RT (the median RT across the first sequence repetition) while the linear slope estimates change in RT, or learning per trial. Model 2 indicates similar variability across participants as in Model 1. The slope estimate though in Model 2 is not statistically significant. Thus, this model does not describe the data better than does Model 1. Figure 6 illustrates the predicted RT outcomes across the 24 repetitions of the sequence.

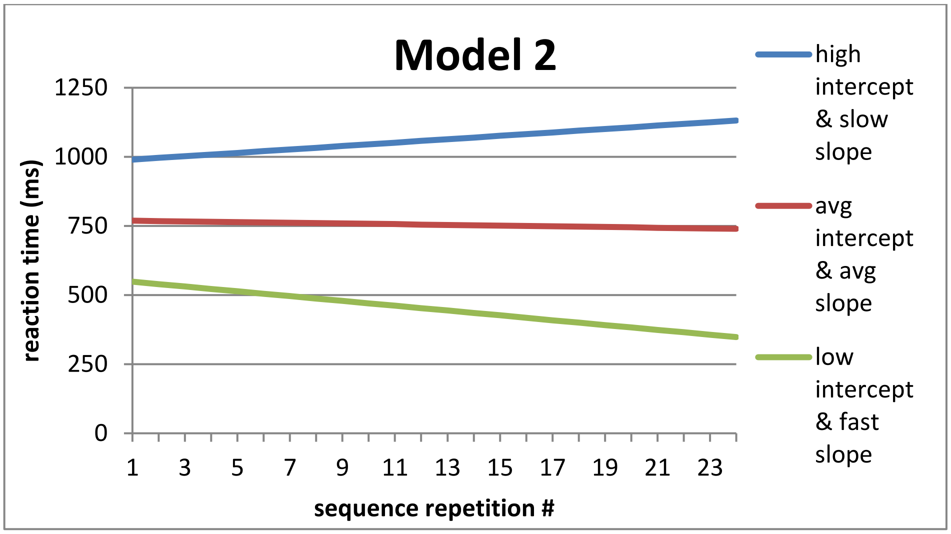

Figure 6. Model 2 predicted outcomes.
This figure illustrates the performance across 24 repetitions of the target sequence predicted by Model 2 for a participant with average initial RT and linear slope, a participant with an initial RT 1SD above the average with a learning slope 1SD slower than average, and a participant with an initial RT 1SD below the average with a learning slope 1SD faster than the average.

3.3.3 Models 3-5: Intercept, Linear Slope, & Language Predictors

Models 3-5 add participants' language ability in each of three different domains (i.e., vocabulary, grammar, and phonological awareness) as predictors. Across Models 3-5, the main effect for these language variables have relatively large standard errors and are not statistically significant in any model. Further, estimates of random variance and deviance indicate these models do not aptly capture the variance within this dataset. In other words, Models 3-5 show non-significant effects of language characteristics contributing to the models of RT growth.

3.3.4 Model 6: Intercept, Linear Slope, & Diagnostic Category

Model 6 adds participants' diagnostic category (i.e., DD only or DD+SLI) as a predictor of initial RT and slope. The main effect of this model has a large standard error and the estimates of random variance indicate that this model does not usefully capture the variance within these data.

4 DISCUSSION

Using the PDH proposed by Ullman & Pierpont as the conceptual framework, grammar is conceptualized as primarily supported by the procedural memory system while vocabulary is supported by the declarative learning and memory system. Among children who struggle to develop language (SLI), grammatical awareness has been identified as a hallmark impairment. Multiple studies have demonstrated a relation between impairment in grammar and deficits in implicit sequence learning, a specific type of procedural learning, among individuals who meet criteria for SLI. Similar implicit sequence learning deficits have also been demonstrated among children who meet criteria for DD. The relation between implicit sequence learning and the hallmark impairment of this disorder, phonological awareness, remains unexamined. Additionally, the base rate of grammatical deficits in children with DD has not always been evaluated, leaving open the question of the underlying links between implicit sequence learning ability and language outcomes across DD and SLI.

To evaluate implicit sequence learning within this unique sample of children who meet criteria for DD or for co-morbid DD+SLI, we first created a model of stable performance across the 24 repetitions of the target sequence (i.e., limited/no learning), which fit these data well, indicating that SRT performance among children with DD and DD+SLI could be represented using only an intercept estimate, without accounting for implicit sequence learning. More importantly, a change in RT across the repetitions of the sequence (Model 2) did not produce a significant slope estimate, and the variability across participants was not reduced from Model 1. Taken together, these models indicate that for these children with DD or DD+SLI, there is little to no demonstrated implicit learning across the 24 repetitions of the sequence. In other words, both children in this sample with DD only and with co-morbid DD+SLI exhibit no implicit sequence learning on this SRT task.

To address the first aim, we evaluated whether implicit sequence learning abilities among children who met criteria for DD only or for DD+SLI are related to grammatical understanding but not to vocabulary abilities, as predicted by the PDH. In these analyses (Model 3 & 4), neither grammar nor vocabulary significantly contributed to the model of implicit sequence learning in terms of intercept and slope. In other words, in this sample of children with DD and DD+SLI, implicit sequence learning does not appear to be related to grammar or to vocabulary. This finding contradicts the present study's hypothesis and theoretical foundation as developed by the PDH, predicting that grammatical understanding is related to procedural learning while vocabulary is related to declarative learning. This result is unexpected given previous findings that grammar and vocabulary are differentially associated with SRT performance. However, the children in this highly co-morbid sample may have broader deficits than children in previous studies. By including less impaired or more typically developing children, resulting in a more diverse range of learning slopes, it is possible that these relations may be more apparent.

Secondly, we explored whether phonological awareness, a hallmark impairment in DD, is related to implicit sequence learning abilities in children with DD and DD+SLI or diagnostic category differentially related to performance on an SRT task. This analysis (Model 5) indicated that phonological awareness was not related to implicit sequence learning intercept or slope. Given the previous finding that grammar and vocabulary did not differentially relate to implicit sequence learning, conclusions cannot be drawn from these data regarding which learning and memory system, declarative or procedural, preferentially supports phonological awareness.

Finally, we evaluated whether implicit sequence learning abilities differed between children who met criteria for DD only and those who met criteria for com-morbid DD+SLI. This model (Model 6) indicated that diagnostic category was not related to implicit sequence learning intercept or slope. This finding may contradict the present study's hypothesis that children with DD will demonstrate less impaired implicit sequence learning relative to children with DD+SLI. However, this result may again be related to the lack of learning across the implicit sequence learning task in both groups. Theoretically, while it appears to support the PDH conceptualization of shared procedural learning deficit across DD and SLI diagnostic categories, control subjects will be necessary to appropriately interpret these results. If typically developing children demonstrate implicit sequence learning across the 24 repetitions on this version of the SRT task, then these results can be interpreted as evidence for equivalent impairment in implicit sequence learning abilities. Thus, if TD children demonstrate substantial implicit sequence learning across the sequence repetitions using this paradigm, it can be more strongly inferred that the DD only and DD+SLI groups demonstrated a shared implicit sequence learning deficit using this paradigm.

On the other hand, if TD children do not exhibit learning across the repetitions, it is possible that the methodology used in this study does not adequately allow for the reliable assessment of implicit sequence learning. While similar keypads have likely been used in previous studies, the standard desk numeric keypad used in the present study may not be sensitive enough to capture subtle variation in RT. In this case, a touchscreen may be helpful to reduce noise in the system (this would also reduce the need for children to translate and transfer what they see on the screen to a keypad below the screen). However, if valid change or response is so clinically small, improvements in the measurement equipment might not be likely to provide clinically useful information.

In addition to mechanical methodology, this study incorporated widely used SRT methods, namely 24 repetitions of a 10-item deterministic sequence. While this approach was informed by previous SRT research, it is possible that these methods interfere with individuals' learning across the task. In particular, there is substantial inconsistency across studies regarding the number of times the sequence is repeated within the SRT task. The present study used 24 repetitions, which is relatively few in context of studies that expose participants to as many as 96 repetitions of a sequence. Predictably, the number of repetitions of the target sequence has been shown to significantly affect the amount of information learned, particularly by individuals who meet clinical criteria. Though some studies have demonstrated implicit sequence learning in both typically developing children and those who meet clinical criteria with as few as 24 repetitions of the sequence, research has also shown that fewer repetitions are related to larger implicit sequence learning difference between TD children and those with SLI. Given that the subjects in the present study met criteria for DD or DD+SLI, it is possible that these children were not able to implicitly learn the sequence in only 24 repetitions, though they may have demonstrated significant learning if exposed to more repetitions of the sequence.

In terms of the number of items in the sequence, the effect of differing sequence lengths may have on participant learning remains unclear. However, it is likely that learning a longer sequence is inherently more difficult than learning a shorter sequence. The present study incorporated the most commonly used sequence length across SRT studies, which has been associated with both positive and negative findings in terms of children's ability to implicit learn a sequence of this length. Thus, the widely used 10-item sequence may have contributed to the lack of learning among the children in the present study; it is possible that they may have demonstrated less impaired implicit learning if a shorter sequence were used.

Finally, while most recent research has examined deterministic sequences, some have used probabilistic sequences. Evidence suggests that implicit sequence learning occurs in both deterministic and probabilistic conditions. Additionally, it is likely that learning a deterministic sequence is inherently a simpler task than learning a probabilistic sequence that varies statistically. Thus, it is improbable that the deterministic format of the sequence used in the present study contributed to the lack of learning observed in this population.

5 CONCLUSION

These analyses indicate that participants who meet criteria for DD only or for DD+SLI did not demonstrate the implicit sequence learning within this SRT paradigm. Results indicated that grammar, vocabulary, and phonological awareness were not related to implicit sequence learning, but given that there was no variance in learning, the lack of relationships is not surprising. Further, the diagnostic categories (DD or DD+SLI) did not differentially relate to implicit sequence learning abilities, but again, the lack of learning made this comparison limited. Overall, children with DD and DD+SLI did not demonstrate, within this SRT task and paradigm, implicit sequence learning, and this pattern was not differentially related to components of language ability or to diagnostic category.

Without TD children's performance on the same task, which would be expected to show systematic implicit learning and change over the 24 sequence repetitions, it is not possible to interpret whether this lack of learning can be attributed to the predicted deficit in implicit learning abilities, or if the methodology employed in this study limited participants' ability to learn the sequence. Thus, it will be critical to explore the learning patterns (i.e., initial RT and slope of RT change across 24 sequence repetitions) within TD children.

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