

Procedural Learning in Adults with and without Developmental Language Disorder:

The Influence of Manual Motor Demands

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**Abstract**

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The purpose of this research project was to determine differences in procedural learning in adults with and without developmental language disorder (DLD) when manual motor output is and is not required for a learning task. DLD is a neurodevelopmental disorder characterized by unexplained deficits in expressive and/or receptive components of language. The Procedural Deficit Hypothesis (PDH) suggests that individuals with DLD possess deficits in procedural learning and memory due to underlying brain structures responsible for both components of implicit learning and linguistic skill. Relatedly, the Sequential Pattern Learning Deficit Hypothesis (SPLDH) proposes that only sequence-based procedural memory and learning is impaired in DLD populations. In the present study, we employed two sequence-based procedural learning tasks to determine the influence of manual motor output demands on procedural learning. A total of 23 participants (4 = DLD; 19 = typical development) engaged in a serial

reaction time task (SRTT) measuring their ability to implicitly learn a visually-presented, 10-element sequence via manual motor output (i.e., keystrokes on a keyboard). These same participants engaged in a visual statistical learning (VSL) task to measure their implicit learning when manual motor output is not demanded. Consistent with the PDH and SPLDH, we hypothesized that adults with DLD would perform worse on motor-dependent sequential learning task when compared to adults with typical development, indicating poorer procedural learning and memory when manual motor output is required. However, we additionally hypothesized that adults with DLD would perform similarly to typically developed adults on the sequential learning task in which manual motor output was not required. Here we present initial results on the preliminary data set. Visual inspection of our initial results indicates that the DLD group performs worse on the SRTT and equivalently on the statistical learning task, consistent with our hypotheses. Statistical analysis did not yield significant results with the current sample size. This study contributes to the existing literature by exploring the influence of motor demands on procedural learning in DLD populations. Implications and future directions are discussed.

**Keywords:** developmental language disorder, procedural learning, sequential pattern learning, motor skills, manual motor skills

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## **Introduction**

### *1.1 Defining DLD*

Developmental language disorder (DLD) is a neurodevelopmental disorder characterized by unexplained deficits in expressive and/or receptive components of language that cannot be attributed to hearing loss, deficits in non-verbal IQ, and/or a lack of access to language in one's environment (Bishop, 2017). Impacting nearly 7% of the pediatric population, DLD is a commonly-occurring difference that holds a poor prognosis for independent improvement (Bishop, 2017; Norbury et al., 2016). Associated challenges of DLD include impairments in phonology (Ehrhorn et al., 2020), morphology and syntax (Fey et al., 2004; Nippold et al., 2009), and macro-level narrative skills (Kuvač Kraljević et al., 2020). Furthermore, these linguistic deficits often result in academic and psychosocial challenges (Fujiki et al., 1996; McGregor, 2020), as well as overall lower quality of life (Eadie et al., 2018; Le et al., 2021).

DLD has previously been studied and diagnosed under the label of Specific Language Impairment (SLI); however, an expert panel concluded that the term “Developmental Language Disorder” more fully captures the heterogeneous features of the disorder and holds more clinical utility (Bishop, 2017). For example, the word “specific” suggests that the child's impairment is limited to language, when in reality, language deficits may co-occur with other neurodevelopmental conditions (e.g., attention deficit hyperactivity disorder, developmental coordination disorder, dyslexia). In contrast, a more general label of “developmental language disorder” encourages more holistic diagnosis and treatment of the child's complete neurological profile. A unified label for childhood language disorders, which have historically received less attention than other neurodevelopmental disorders, such as dyslexia, autism spectrum disorder, and attention deficit hyperactivity disorder, is critical for research and policy. Arguably most

important, a consistent label is conducive for the identification and treatment of individuals with different profiles of language challenges (Bishop, 2017).

### *1.2 DLD & Dyslexia*

As discussed above, DLD may also co-occur with other neurodevelopmental conditions, including dyslexia (Bishop, 2017). Characterized by poor decoding (i.e., the mapping of sounds onto orthography in order to read a word) and encoding (i.e., mapping of orthography onto sounds in order to spell a word), dyslexia is often considered an impairment in the phonological domain of language (Adlof & Hogan, 2018). In contrast, children with DLD typically experience deficits across two or more domains of language, such as phonology, morphology, or syntax (Bishop, 2017). Much like DLD, dyslexia's presence cannot be explained by other factors such as visual deficits, medical conditions, or a lack of appropriate environmental stimulation (Adlof & Hogan, 2018).

Catts and colleagues (2005) propose that dyslexia and DLD are distinct conditions that may frequently co-occur. In a sample of over 500 kindergarten students, the researchers found that 17% to 36% of children with a diagnosis of DLD met criteria for a dyslexia diagnosis. (The range can be explained by varying criteria for diagnosis of dyslexia.) Subsequent research has supported the distinction of the two conditions while acknowledging they frequently occur in tandem with each other (Adlof & Hogan, 2018).

## Fully Distinct Hypothesis (Catts et. al, 2005)

		Phonological Abilities	
		<i>Poor</i>	<i>Good</i>
Nonphonological Language Abilities	<i>Good</i>	Dyslexia	Typically Developing Reading and Language
	<i>Poor</i>	Dyslexia + DLD	DLD

Figure 1.1 A 2x2 table describes the relationship between phonological abilities and nonphonological abilities and their mapping onto diagnostic labels (Catts et al., 2005).

Despite the fact that an individual with dyslexia's primary impairment lies in phonology, some evidence suggests that children with this diagnosis may also display relatively weaker language skills in comparison to typically developing peers (Adlof et al., 2017; Bishop et al., 2009). For example, Bishop and colleagues (2009) found that children with dyslexia who did not meet clinical qualifications for DLD still displayed significantly poorer skills in vocabulary, sentence repetition, and syntax comprehension when compared to typically developing peers. Notably, test scores of these skills fell within normal limits, failing to raise clinical red flags; however, this study and others suggest nuances in the language skills of individuals with dyslexia, beyond known phonological deficits. Overall, current research suggests a meaningful relationship between the diagnoses of DLD and dyslexia.

### *1.3 DLD in Adult Populations*

Although DLD is most frequently diagnosed in childhood, language deficits and associated challenges may persist into adolescence and adulthood. Del Tufo and Earle (2020) suggest that college students with a history of DLD continued to demonstrate poor verbal working memory and speeded sentence-level reading, consistent with skill deficits present in younger children with DLD. Adult men with DLD have also been found to demonstrate poorer verbal short-term memory and phonological processing compared to their siblings and other non-related, age-matched adults (Clegg et al., 2005). Much like their younger counterparts, adolescents and adults with DLD may also experience adverse psychosocial outcomes, such as poorer friendship quality and increased risk of psychiatric disorders (Clegg et al., 2005; Conti-Ramsden & Botting, 2008; Law et al., 2009). Educational achievement and employment prospects may also be negatively impacted in adults with DLD (Conti-Ramsden et al., 2018; Durkin et al., 2012; Law et al., 2009). Taken together, current research on adults with DLD presents a compelling argument of the persistence of language-related deficits and associated challenges into early adulthood and beyond.

### *1.4 Neural Bases of Learning & Language*

Two distinct processes of learning and memory contribute to typical acquisition and use of language: declarative and procedural (Ullman, 2001, 2004). Declarative memory encompasses our knowledge of events and learned facts and is considered to be explicit, or able to be consciously accessed. Conversely, procedural learning and memory entails the abilities to establish and maintain motor and cognitive skills, including learning of sequences and rules. Because knowledge of most procedures, such as riding a bike or typing, typically cannot be consciously accessed, procedural memory is considered to be a type of implicit memory (Squire

& Zola-Morgan, 1991; Ullman & Pierpont, 2005). In the context of language, declarative memory is thought to support semantic knowledge such as vocabulary (or one's "mental lexicon"), while procedural learning is thought to contribute to our acquisition of phonology and grammar (Knowlton et al., 1996; Poldrack et al., 1999; Ullman, 2001, 2004).

Importantly, declarative and procedural systems are thought to be (somewhat) neurologically distinct. While declarative learning is largely dependent on the medial temporal lobe, the procedural learning and memory system is comprised of several neuroanatomical structures and the connections that exist between them (Hikosaka et al., 1999; Rizzolatti et al., 2001; Ullman, 2001, 2004). Especially critical components are the putamen and caudate nucleus, subcortical structures that comprise the striatum within the basal ganglia. These structures are closely linked with areas of the frontal lobe, including the primary motor cortex, ventral premotor cortex, and the supplementary motor area (Alexander et al., 1986; Middleton & Strick, 2000). Together, these structures form frontal-basal ganglia circuits, allowing subcortical structures to communicate with frontal portions of the brain. Specifically, the putamen and caudate nucleus are responsible for sending excitatory and inhibitory signals to structures in the cortex, contributing to motor regulation (Albin et al., 1989; Obeso et al., 2008). Imbalances between these excitatory and inhibitory signals is associated with abnormal motor behavior that is characteristic in disorders such as Parkinson's Disease, Attention Deficit Hyperactivity Disorder, and other developmental or acquired disorders (Bradshaw & Sheppard, 2000; Obeso et al., 2008). The structure of the caudate nucleus is thought to be different in DLD (Badcock et al., 2012; Cler et al., 2020; Herbert et al., 2003; Krishnan, Cler, et al., 2021), although evidence is not yet conclusive (Girbau-Massana et al., 2014; Pigdon et al., 2019).

### 1.5 Measuring Procedural Learning

Procedural learning and memory can be measured by a variety of methods. By far the most popular in existing literature is the Serial Reaction Time Test (SRTT) (Robertson, 2007). An SRTT requires a participant to respond to a cue with a specific movement (typically, a press of a button) as fast as possible without trying to anticipate the movement. Unbeknownst to the participant, in some blocks of stimuli, the order of targets/movements is in a specific sequence, which allows participants to learn the order via practice. In other blocks, the stimuli occur in a pseudorandom order. Procedural memory is examined by comparing the differences in response time between sequenced blocks and random blocks, known as the “S-R difference”. Importantly, the SRTT assumes that an individual’s response time to a stimulus is indicative of their learning, wherein reduced response times indicate increased familiarity/learning. If procedural learning were to take place, a decrease in response time would be demonstrated across sequenced blocks (due to implicit learning of the sequence). This same decrease in RT would not be present in random blocks, as there is no sequence to implicitly learn (Krakauer et al., 2019).

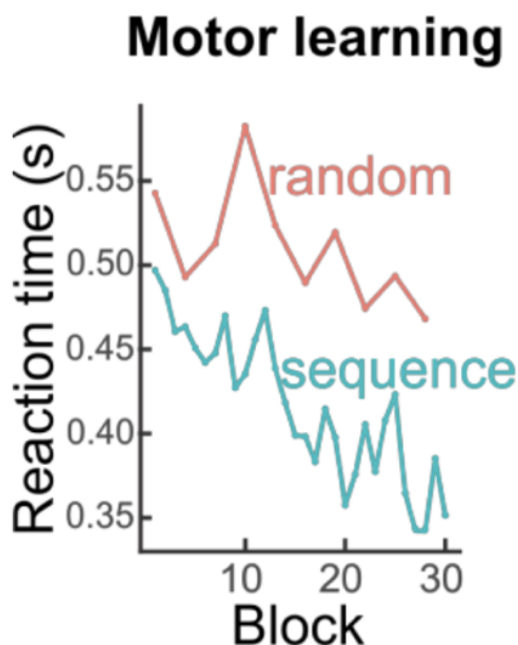


Figure 1.2 Pilot data showing reaction time decreases (indicating an increase in performance) on sequenced blocks as a sequence is implicitly learned over time. Reaction time remains higher across random blocks due to lack of a sequence to implicitly learn.

Shortcomings of the SRTT include an inability to distinguish a participant's reaction time from their movement time, making it impossible to parse out improved knowledge of the sequence order versus improvements in the execution of the movement to indicate one's response. Additionally, in an SRTT, accuracy is defined binarily (i.e., either "correct" or "incorrect") without consideration of the acuity of a movement. Importantly for our question, the design of the SRTT also makes it impossible to distinguish the ability to *learn* the sequence from the ability to *perform* the sequence; motor differences in the absence of sequential learning differences could also be interpreted as a failure to learn the sequence. Despite these downfalls, SRTT is a widely-adopted method as it has demonstrated links to the procedural memory system (Clark et al., 2014; Hardwick et al., 2013). Additionally, it allows for implicit learning of the sequence in the absence of explicit knowledge of the entire sequence (Krakauer et al., 2019).

While SRTTs typically require a manual motor output to engage in learning (e.g., button presses), non-motor dependent tasks may also be used to examine procedural learning. In one such task, the visual statistical learning (VSL) paradigm, participants undergo two distinct phases: a "familiarization phase" and a "test phase". Within the familiarization phase, participants are presented with a stream of stimuli that contain repeated triplets (e.g., short sequences). During the presentation, participants are sometimes asked to perform a cover task, such as pressing a button every time a triangle appears, in order to promote attention to the stream and encourage implicit familiarization of the sequence. (Importantly, this cover task is not required for learning of the sequence). After the stream has been fully presented, participants enter the test phase, in which they demonstrate learning by accurately identifying which stimuli are most likely to occur in a particular order. While both an SRTT and a VSL paradigm measure

learning of a sequence, the latter task is largely perceptual in nature and does not require manual motor output to engage in the learning process (Krakauer et al., 2019)

### *1.6 Theories of DLD*

Due to the impact of DLD across the lifespan, much research has been devoted to understanding its etiology. While some theories characterize DLD as either the result of grammar-specific deficits or non-linguistic processing deficits, others attempt to capture both linguistic and non-linguistic deficits associated with the disorder. A prominent explanation for the etiology of DLD, the Procedural Deficit Hypothesis (PDH) emphasizes that the same structures recruited for procedural memory and learning tasks (as discussed above) support linguistic functions such as grammar and lexical retrieval (Ullman & Pierpont, 2005). Critical to the theory is the shared neurological underpinnings of both language and procedural learning. According to the PDH, differences in particular neuroanatomical structures may manifest as deficits in both procedural learning and linguistic skills; as a result, the theory posits that many individuals with DLD demonstrate deficits in procedural learning and memory (Ullman & Pierpont, 2005).

The PDH has been supported and expanded upon by a variety of recent research (Evans & Ullman, 2016; Hamrick et al., 2018; Nicolson & Fawcett, 2007, 2011). Additionally, several meta-analyses have addressed the relationship between procedural learning and DLD. Clark and Lum (2017) found that SRTT performance was moderated by a DLD diagnosis, while Lum and colleagues (2014) found that individuals with DLD demonstrated poorer procedural learning than typically developing (TD) populations, as measured by SRTTs. Additionally, Lum, Ullman, and Conti-Ramsden (2013) determined that individuals with dyslexia displayed worse

performance on SRTTs compared to typically developing peers, indicating poorer procedural memory and learning.

However, the PDH has not existed without concern and criticism. For example, West and colleagues (2018) failed to find relationships between measures of implicit learning and language, literacy, and arithmetic attainment in a representative sample of school-age children. However, later research has called into question West's methodology; namely, the authors presumably studied a largely typically-developing population and utilized tasks that did not clearly probe procedural learning (Conway et al., 2019).

An alternative to the PDH, the Sequential Pattern Learning Deficit Hypothesis (SPLDH), proposes that not all procedural learning is impaired within DLD populations (Gerken et al., 2021; Goffman & Gerken, 2020; Hsu & Bishop, 2014). Rather, the theory proposes that only sequence-based procedural learning tasks pose difficulty to individuals with DLD. For example, Hsu and Bishop (2014) studied both sequential and non-sequential procedural learning in children with and without DLD. In an SRTT (i.e., a task that measures sequence-based procedural learning), children with DLD performed poorer than typically developing peers but similarly to a grammar-matched control group (i.e., a group of younger children without DLD who displayed similar grammar skills to the older children with DLD). However, on a pursuit rotor task (i.e., a procedural learning task that did not incorporate sequences), children with DLD performed comparably to typically developing peers, and both groups outperformed the grammar-matched control group. Gerken, Plante, and Goffman (2021) also found evidence for the SPLDH in their study of adults with and without DLD. Their experiment entailed the learning of two artificial languages, one of which required computation of sequential dependencies to learn and one of which did not. As hypothesized, both groups demonstrated

equally robust learning of the language that did not incorporate sequential dependencies. The authors argue that this research supports the SPLDH by demonstrating the ability of adults with DLD to learn an artificial language that does not require sequential dependencies; in other words, procedural learning of non-sequential tasks was intact in adults with DLD. Continued exploration of procedural learning and memory in DLD populations, particularly with valid and reliable measures, is warranted for increased understanding of the underlying causes of DLD (Krishnan & Watkins, 2019).

### *1.7 Motor Learning Skills in DLD Populations*

Beyond linguistic impairments, current research suggests differences in motor profiles between individuals with and without DLD. For example, as discussed above, differences have emerged on SRTTs and other sequence-based procedural learning tasks between DLD and typically developing populations (Clark & Lum, 2017a; Lum et al., 2013, 2014). Beyond this literature, DLD has been found to be associated with poorer fine and gross motor skills (Hill, 2001; Preis et al., 1997) and delayed motor development (Diepeveen et al., 2018) in pediatric populations. Children with DLD have poor motor performance across many tests of gross and fine motor skills (Hill, 2001), including balance, peg moving, and learning to perform manual signs (Hill, 2001; Krishnan, Asaridou, et al., 2021; Vuolo et al., 2017).

Therefore, further research should be conducted to determine if deficits on tasks designed to measure procedural learning stem from such differences in motor profiles. There has been some evidence to suggest that procedural, sequence-based learning is not impaired when the learning does not require manual output. For example, Lammertink and colleagues (2020) failed to find evidence for a relationship between performance on an explicit VSL task (i.e., a task that did not require manual motor output such as button presses, for procedural learning) and a DLD

diagnosis. (We classify the task as “explicit” because participants were notified prior to starting the task that there was a pattern. Informing participants of the existence of a pattern allows them to utilize explicit learning and memory processes to learn the pattern.) Lum and Clarke (2021) tested sequence learning of children with and without DLD in both the manual and oculomotor domain. Children with DLD did not display sequence learning in the manual domain, while their TD peers did display manual sequence learning. However, both groups demonstrated learning in the oculomotor domain, suggesting that children with DLD may have procedural learning deficits specific to manual tasks and skills. Finally, Gabriel and colleagues (2012) detected differences in performance between children with DLD and TD children on a traditional SRTT paradigm, but when the task was changed to touch screen format (lessening cognitive and motor demands due to direct pressing of the stimulus, rather than a button that corresponded to the stimulus), reaction time and accuracy rates of children with DLD approximated TD peers.

Differences in procedural learning may also stem from modality-specific learning deficits. A meta-analysis by Lammertink and colleagues (2017) found significant differences in statistical regularity detection skills in the auditory domain between children and young teenagers with and without DLD. Similar findings have been revealed in studies using auditory artificial grammar learning paradigms. For example, Plante, Gómez, and Gerken (2002) found that adults with language and/or learning disabilities performed below a comparison group on a test of artificial grammar learning (identifying grammatical versus ungrammatical word strings) in the auditory modality. Alternatively, modality may not matter; Obeid and colleagues’ meta-analysis (2016) of a variety of “statistical” learning tasks (including SRTT) revealed that TD groups showed increased learning in comparison to peers with DLD across both auditory and visual task modalities. We have chosen a visual modality for our statistical learning task in order

to align with the visual nature of the SRTT and allow for a more direct insight into the influence of manual motor demands on visually-based learning.

### *1.8 Contributions, Research Questions, & Hypotheses*

This study contributes to the existing literature by exploring the influence of motor demands on procedural learning in DLD populations. Importantly, understanding the learning principles and skills of individuals with DLD holds clinically-relevant implications for informed treatment and improved outcomes (Plante & Gómez, 2018). While the PDH and SPLDH focus on the impairment of procedural learning as a whole and sequence-based procedural learning, respectively, our interest lies in differences in sequence-based procedural learning when manual motor output is required (i.e., an SRTT) versus when manual motor output is not required (i.e., VSL task). We propose the following research questions and corresponding hypotheses:

1. Do significant differences in procedural learning and memory skills exist between adults with DLD and adults with a history of TD on a sequence-based task that requires manual motor output?

We hypothesized that there would be significant differences between the differences in performance on a SRTT, with adults with a history of TD demonstrating further decreased reaction times than adults with DLD on the task. This will indicate differences in procedural learning and memory on a sequence-based task that requires manual motor output, with adults with a history of TD demonstrating more robust learning and memory than adults with DLD.

2. Do significant differences in procedural learning and memory skills exist between adults with DLD and adults with a history of TD on a sequence-based task that does not require manual motor output?

We hypothesized that there would be no significant differences between the performance of adults with DLD and adults with a history of TD on a VSL task, indicating comparably robust procedural learning and memory on a sequence-based task that does not require manual motor output.

Overall, we predicted that sequence-based procedural learning would be impaired in adults with DLD when manual motor output is required; however, we hypothesized that this impairment would not exist when manual motor output is not demanded as a function of the learning task or as part of the evaluation of performance.

## **Methods**

### *2.1 Design*

The present study employed an experimental design with between-group comparisons. The independent variable was category membership within a DLD or typically-developing group; category membership was determined using the Fidler method (Fidler et al., 2011). Commonly used in the literature to identify adults with DLD (particularly those who were not identified or diagnosed in childhood), the Fidler method utilizes the following measures: 1) a 44-item modified token test in which participants follow verbal directions (De Renzi & Faglioni, 1978; Morice & McNicol, 1985), 2) a 15-word spelling test, and 3) the Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF-4) Word Definitions subtest (Semel, 2003). See the Appendix for a list of tasks and scoring method to determine category membership.

Dependent variables included differences in reaction time on a novel serial reaction time task (SRTT) and accuracy on a visual statistical learning (VSL) task. These tasks indicate sequence-based procedural learning when manual motor output is and is not required, respectively.

## *2.2 Participants*

We recruited 23 individuals, 19 with a history of typical development (TD) and 4 with a designation of DLD, as determined by the Fidler method (discussed above). All participants were native English speakers (i.e., acquired English below the age of 2) between the ages of 18-45 years. Participants were primarily recruited from the University of Washington community and greater Seattle area, although the virtual nature of all experiment tasks allowed for wider recruitment across the United States.

Recruitment methods included posting physical and digital flyers around university campuses, community college campuses, social media pages for research participation, and social media pages for dyslexia/writing support. Individuals were recruited as potential DLD participants if they reported a history of speech/language delays, reading or writing difficulty, and/or challenges following verbal or written directions; however, they were only included within the DLD group if identified as such by the Fidler method. Additionally, one participant recruited as typically developing with no history of speech or language difficulties was identified as being in the DLD group. This occurrence was somewhat expected given the prevalence of DLD and the generally low rates of diagnosis and knowledge of the disorder.

	<b>TD</b>	<b>DLD</b>
<b>N</b>	19	4
<b>Age</b>	Range: 19–35 years Mean: 22.5	Range: 21–35 years Mean: 26.3
<b>Gender</b>	Woman: 16 Man: 1 Nonbinary: 2	Woman: 3 Man: 1 Nonbinary: 0
<b>Fidler Score</b> <i>negative = TD, positive=DLD</i>	Range: -1.98 – -.54 Mean: -1.37	Range: 0.39–1.6 Mean: 1.1
<b>Attend(ed) College</b>	100%	100%

Table 2.1 Participant Characteristics

Due to technical error, VSL data were unavailable for 3 participants with a history of typical development. Therefore, we report data for 23 individuals in the SRTT (19 = TD, 4 = DLD) and 20 individuals in the VSL (16 = TD, 4 = DLD).

### 2.3 Materials

The SRTT employed in the present study was modeled after Lammertink et al. (2020) and programmed on Pavlovia.org by our laboratory (Bridges et al., 2020). Participants were instructed to place four fingers of their dominant hand onto four keys of a keyboard and press the corresponding button when one of four areas of their screen changes colors (i.e., stimuli presentation). The stimulus was continuously present until the correct button was pressed. To prevent participants from selecting incorrect responses simply to finish the task more quickly, the next stimulus was not presented until the correct corresponding button for the current stimulus is pressed. An inter-stimulus interval of 250 milliseconds occurred between selection of the correct button and presentation of the next stimulus. Participants were asked to respond to each stimulus presentation with a button press as fast and accurately as possible. One button press constituted a single trial of the SRTT.

Following the Lammertink (2020) paradigm, each participant completed seven blocks of keypresses, in which the first and sixth blocks were pseudorandomly ordered keypresses with 20 and 60 keypresses respectively. The remaining blocks were sequence blocks that contained one of two different 10-element sequence of stimuli presentations modeled after Lammertink et al. (2020) and Clark and Lum (2017b). In a variation from the original Lammertink (2020) paradigm, blocks 2, 3, 4, 5, and 7 (i.e., the sequenced blocks) also incorporated 10 to 15 pseudorandom keypresses after every two sequence repetitions (or every 20 keypresses). This was included to deter explicit knowledge of the presence of a sequence, and reaction time on these keypresses were not analyzed for the purposes of this study. For implications of this methodological design, please see the discussion section.

The sequences were 4-2-3-1-2-4-3-1-4-3 (Lammertink et al., 2020) or 3-4-1-2-4-1-3-4-2-1 (Clark & Lum, 2017b), in which each number was mapped to one of the boxes on the screen, starting with 1 on the far left and moving left to right. The sequences were designed such that no natural sequences occurred (e.g., 1-2-3, 3-2-1) and each number (1-4) is repeated two to three times. Participants were randomly assigned one of the sequences. Fifty percent of the DLD sample received the first sequence while the remaining 50% received the second, and 58% of the TD sample received the first sequence while the remaining 42% received the second. The measure of interest on the SRTT was the difference in mean reaction time between the final random block (i.e., block 6) and final sequenced block (i.e., block 7) (Reaction Time of  $R_F$  – Reaction Time of  $S_F$ ). We refer to this difference as the motor learning index, or MLI (see Figure 2.1). In other words, we intended to isolate the difference in reaction times when a sequence was present versus when it was not.

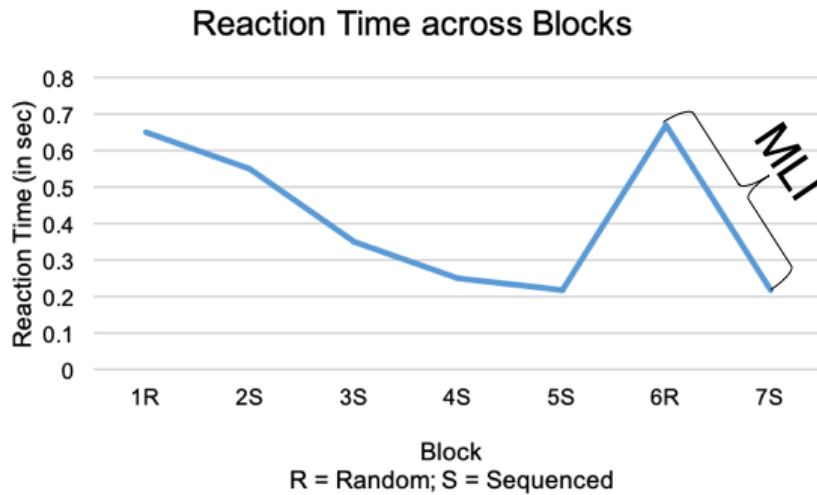


Figure 2.1 Visualization of hypothetical data displaying the expected differences in reaction times across blocks of the SRTT. The difference in mean time between the final random block and the final sequenced block represents the motor learning index (MLI).

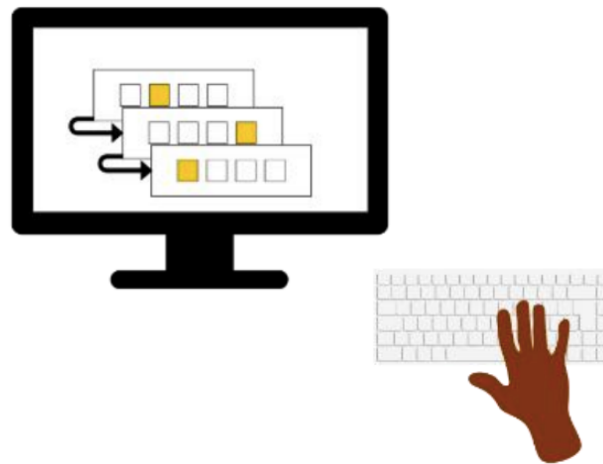


Figure 2.2 A change in the block's color (from white to yellow) constitutes a stimulus presentation. Participants are instructed to press the keyboard button that corresponds with the location of the stimulus presentation as quickly as possible without anticipating or guessing.

After completion of the SRTT, participants took part in a probe for explicit knowledge of the sequence. The probe consisted of a yes/no question (i.e., “Did you notice anything in particular about any of the keypresses?”) followed by disclosure of the presence of a sequence. Participants

then completed a 30-trial free-recall in which they were instructed to attempt to reproduce the sequence. The procedures for the probe of explicit knowledge were modeled after Desmottes et al. (2016). These data were not analyzed for the purposes of the present project.

The novel VSL employed in the present study was modeled after Fiser and Aslin (2002) and programmed on Pavlovia.org (Bridges et al., 2020). The VSL task consisted of two phases: the familiarization phase and the test phase. During the familiarization phase, participants were instructed to attend to a stream of novel shape stimuli which were presented one-by-one on the screen for a duration of 600ms with an inter-stimulus interval of 200ms. Unbeknownst to participants, the order of the shape stimuli followed a sequence. There were a total of 12 distinct shape stimuli, which were grouped into four triplets (e.g. A-B-C, D-E-F, G-H-I, J-K-L) wherein the first shape of the triplet was always followed by the second and third (e.g., A was always followed by B followed by C). During the familiarization stream, shape triplets followed one another with equal probability, with the stipulation that a triplet may not repeat itself (e.g., A-B-C may not be immediately followed by A-B-C). In order to promote attention to the stream, a cover task (i.e., pressing a key every time two of the novel shape stimuli occurring consecutively) was added to the original Fiser and Aslin (2002) design, following Turk-Browne, Jungé, and Scholl (Turk-Browne et al., 2005). To facilitate this task, the final item in a triplet was randomly repeated a total of 48 times within the entire familiarization phase (e.g., A-B-C-C). Because the original triplet remained intact within the stream, we did not expect this repetition to interfere with learning. The familiarization phase lasted six minutes for a total of 624 stimulus presentations (576 true stimulus presentations and 48 repetitions to facilitate the cover task).

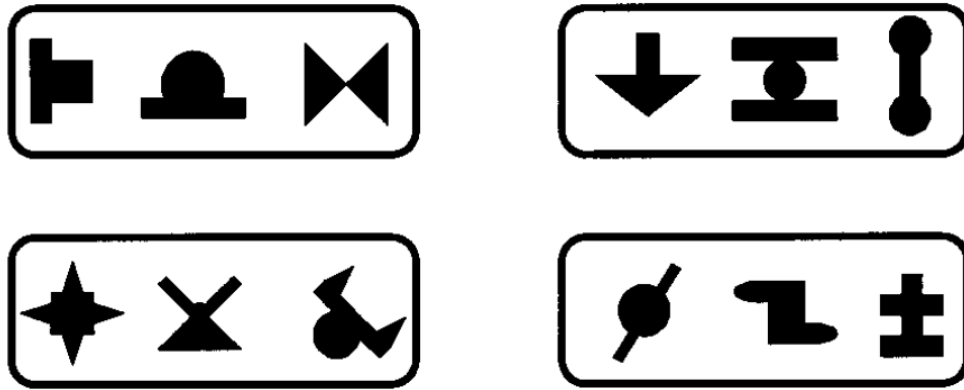


Figure 2.3 The twelve novel shape stimuli randomly grouped into four triplets (Fiser & Aslin, 2002). Shape to triplet assignments were randomly determined for each participant. Rectangular boxes are for grouping purposes only.

Following the familiarization phase, participants underwent a test phase. The test phase consisted of a two-interval forced-choice task that asked participants to select the most familiar sequence based on the previous familiarization phase. Options included a “true” triplet (i.e., one of the four options presented within the stream) as well as a foil triplet, or a random combination of three of the original twelve shapes that never occurred within the familiarization phase (e.g., G-B-K). The four true triplets were each tested against four randomly generated foil triplets in both left and right positions for a total of 32 forced-choice tasks. The triplet options were presented one-by-one in the same manner as the familiarization tasks, beginning with presentation of the left triplet, then the right triplet, then the left triplet again. Participants indicated their choice by pressing a button on their keyboard that corresponded with either the first or second option. They were given unlimited time to respond, but most participants responded within 1 to 2 seconds after the presentation of the options. An accurate response was considered the selection of the true triplet, as this sequence occurred in the familiarization phase whereas the foil triplet did not. The measure of interest was accuracy on the test phase task.

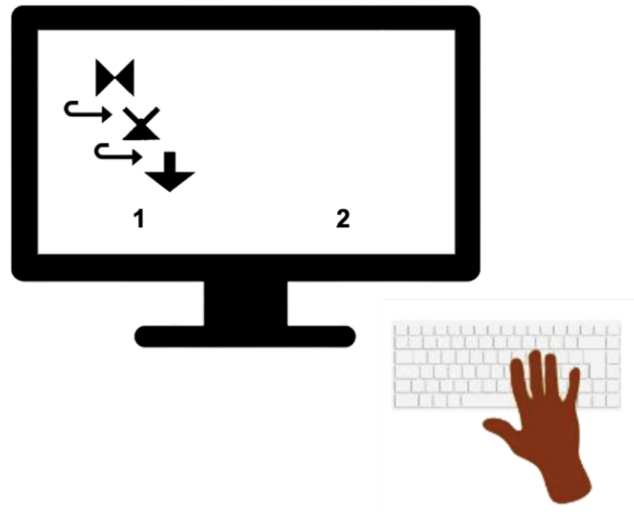


Figure 2.4 Participants were tasked with identifying the true triplet from the foil triplet. Triplets were presented in the same manner as the familiarization phase: one stimulus (shape) at a time. The left triplet was presented first, then the right triplet, then the left triplet again. Participants indicated their choice by pressing a corresponding key on the keyboard.

#### *2.4 Procedures*

Due to the COVID-19 pandemic, all data collection took place online. All participants underwent informed consent procedures prior to commencement of testing. Participation in all study activities took approximately 90 to 120 minutes and was completed within one session. Participants had the option to withdraw from the tests procedures at any time they desired. Participants were compensated for their time. All procedures were approved by the University of Washington IRB.

#### *2.5 Analyses*

Initial data cleaning and analysis was performed in R (4.0.2). Microsoft Excel was used to complete statistical analyses. Unpaired, one sided t-tests were used to compare reaction time differences on the SRTT (S-R;  $DLD < TD$ ) and accuracy on the VSL task ( $DLD < TD$ ) between groups in order to identify differences in procedural learning. An *a priori* power analysis using

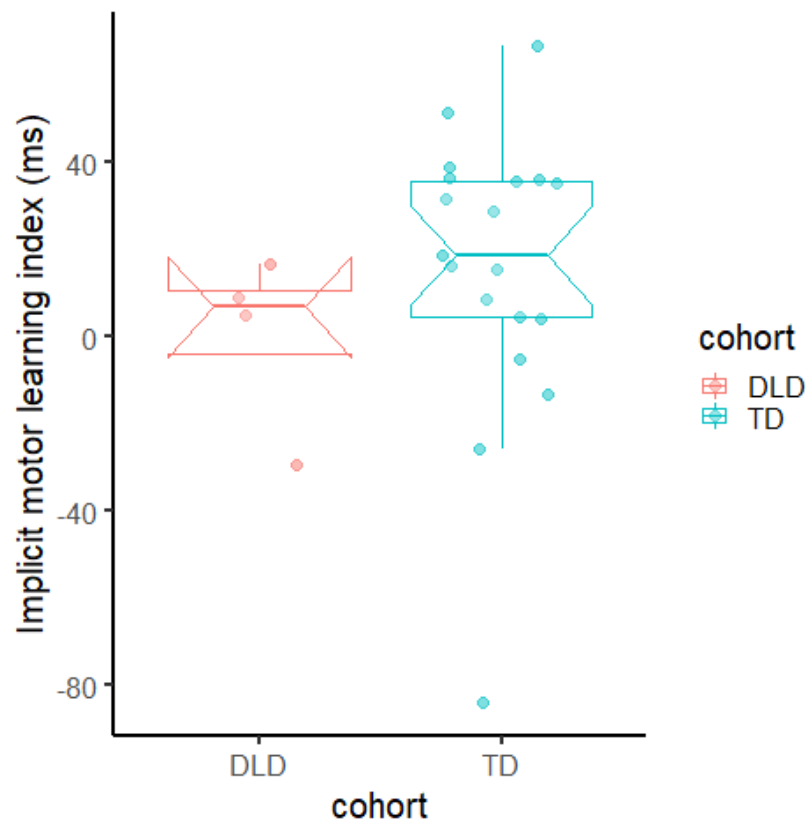
GPower determined that with 42 participants (21 = DLD; 21 = typical development), a power of .8, and alpha of .05, we would be able to detect large effect sizes (Cohen's  $d = 0.8$ ) between the groups. Smaller effects would not be detected.

## Results

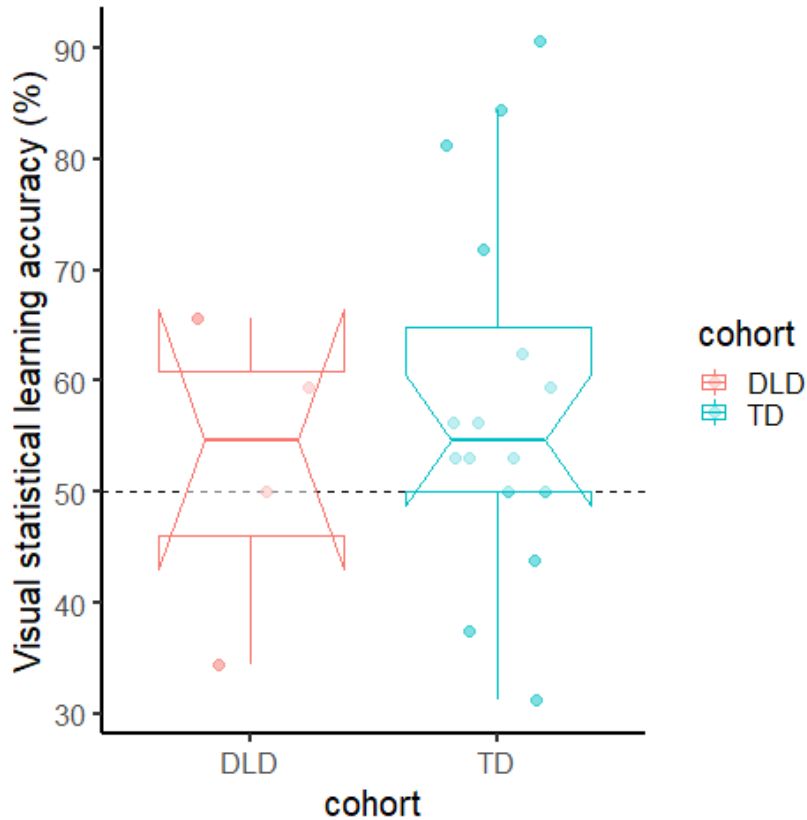
The aim of RQ1 was to determine differences in procedural learning and memory skills between adults with DLD and adults with a history of TD on a task that required manual motor output. The final “motor learning index” was defined as the average reaction time of correct responses during the final random block minus the average reaction time of correct responses during the final sequential block (ignoring the interstitial pseudorandom presses to prevent explicit learning). As shown in Figure 3.1, the TD group demonstrated motor learning on this implicit task, indicated by decreased reaction times during the sequential block ( $M = 15.7$  ms difference;  $SD = 33$  ms). On average, the DLD group did not demonstrate motor learning ( $M = 0.1$  ms,  $SD = 20.4$  ms). However, a one-sided t-test revealed no significant differences between the groups on this task,  $t(22) = 1.174, p = .139$ .

The aim of RQ2 was to determine differences in procedural learning and memory skills between adults with DLD and adults with a history of TD on a task that did not require manual motor output. Both groups performed above chance on average, although individual performance varied (see Figure 3.2). The TD group demonstrated higher accuracy ( $M = 57.7\%$ ,  $SD = 16.2\%$ ) than the DLD group ( $M = 52.3\%$ ,  $SD = 13.9\%$ ). A one-sided t-test revealed no significant effects between accuracy on the VSL forced choice task for of the two groups,  $t(19) = 0.685, p = .262$ .

The aim of RQ2 was to determine differences in procedural learning and memory skills between adults with DLD and adults with a history of TD on a task that did not require manual motor output. Both groups performed above chance on average, although individual performance varied (see Figure 3.2). The TD group demonstrated higher accuracy ( $M = 57.7\%$ ,  $SD = 16.2\%$ ) than the DLD group ( $M = 52.3\%$ ,  $SD = 13.9\%$ ). A one-sided t-test revealed no significant effects between accuracy on the VSL forced choice task for of the two groups,  $t(19) = 0.685, p = .262$ .



**Figure 3.1** Distribution of individual differences on the motor learning index (i.e., mean reaction time between the final random block and final sequence block) of the SRTT. No significant differences were found between the two groups' performances on the task.



**Figure 3.2** Distribution of individual accuracies on the VSL forced choice task. No significant differences were found between the two groups' performances on the task.

## Discussion

### 4.1 Implications of Findings

The primary aim of this study was to investigate the influence of manual motor demands on procedural learning abilities of adults with and without developmental language disorder. Our data collection is as yet ongoing. While statistical analysis yielded no significant differences in task performance between groups on the SRTT or VSL task, we anticipate this lack of difference is largely due to a small sample size; our *a priori* power analyses suggested that 21 participants per group would be needed to identify large effects.

#### *4.1.1 Implications of differences on SRTT but not VSL*

Numerically, our initial data indicate that there may be a difference in motor learning indices between TD and DLD participants on the SRTT. If this were found in conjunction with no significant differences in accuracy on the VSL task, it would confirm our hypothesis that differences in procedural learning in the DLD population are impacted by a task's manual motor demands.

This potential finding would add important nuance to current theories of procedural learning skills in individuals with DLD. While prominent ideas suggest that procedural learning is wholly impaired across persons with DLD (Ullman & Pierpont, 2005) or that impairment is specific to sequence-based learning (Gerken et al., 2021; Hsu & Bishop, 2014), these theories do not account for known motor deficits in the DLD population (Hill, 2001; Preis et al., 1997). Our project sought to isolate procedural learning that required manual movement as a part of the learning process from procedural learning that did not require manual movements in order to detect possible differences and further contribute to our understanding of the nature of impairments in DLD.

#### *4.1.2 Implications of differences on SRTT and VSL*

If we should find significant differences in both the SRTT and the VSL, this may suggest that both manually-based and nonmanually-based procedural learning is impaired in persons with DLD. These results would remain consistent with both the Procedural Deficit Hypothesis (Ullman & Pierpont, 2005) and the Sequential Pattern Learning Deficit Hypothesis (Hsu & Bishop, 2014).

#### *4.1.3 Implications of no group differences*

It is possible that our future findings would yield no significant differences between group performance on either task. If this were found, it would suggest that persons with DLD were able to approximate the procedural learning skills of persons with typical development on the specific tasks included in this project. This would indicate that either their abilities are typical on these tasks, or that our particular paradigm is not sensitive to any small differences that may exist (as indeed our *a priori* power analysis indicated that only large differences would be detected). This result would not be wholly unexpected, as indeed some previous work has suggested that VSL paradigms are generally variable and possibly unreliable (see *4.3 Adjustments to the Visual Statistical Learning Task*), and we modified the SRTT by inserting many more pseudorandom keypresses (see *4.2 Adjustments to the Serial Reaction Time Task*). While this was successful in reducing the amount of explicit knowledge of the sequence that participants reported, it also likely reduced their learning. This could affect the sensitivity of the paradigm to detecting group differences.

#### *4.2 Adjustments to the Serial Reaction Time Task*

As discussed in the methods section, the implicit SRTT incorporated 10 to 15 pseudorandom keypresses after the completion of every 2 sequences (or 20 sequenced keypresses) in all sequenced blocks. Though this varied from Lammertink et al.'s (2020) original design, we opted to include these pseudorandom keypresses to obscure explicit (rather than implicit) knowledge of the sequence and deter the use of neurological processes specific to explicit learning. During the project's piloting phase, 6 out of 9 participants explicitly reported the presence of a pattern or sequence, while the remaining 3 pilot participants made mention of "repeats" or "repetitions" during the task.

After adoption of the current SRTT paradigm (i.e., the version that incorporated the additional pseudorandom keypresses), only 5 out of 23 participants explicitly reported the presence of a “pattern” or “sequence”, while an additional 2 speculated that there may have been a pattern. However, while the inclusion of these pseudorandom keypresses lessened explicit knowledge of the sequence across the groups, learning of the sequences was also greatly impacted, as demonstrated by the relatively smaller motor learning index on the SRTT that included the extra pseudorandom keypresses (see Figure 4.1). Therefore, it is currently unclear if either group is capable of gaining truly implicit knowledge of the sequence on the current paradigm.

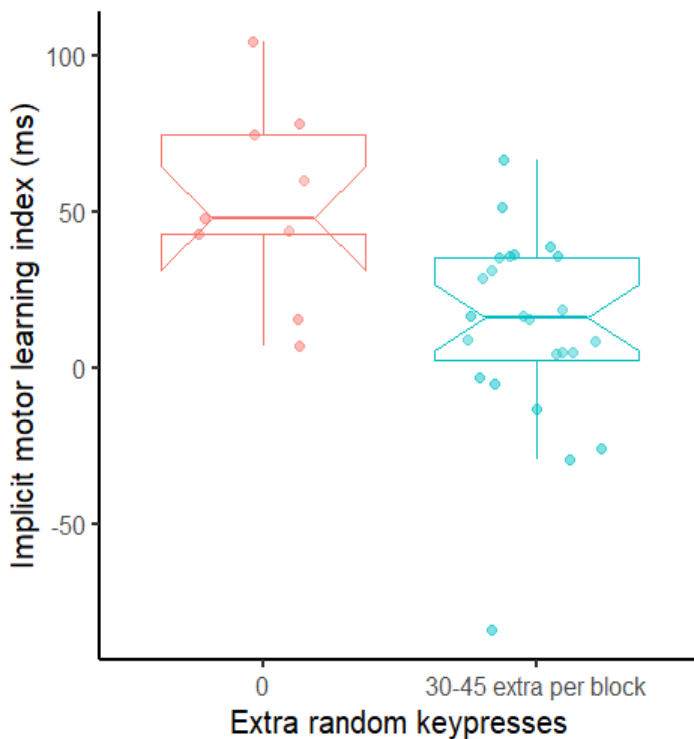


Figure 4.1 Distribution of individual motor learning indices on two different iterations of the SRTT: a version with no pseudorandom keypresses inserted into sequenced blocks and a version with 30-45 pseudorandom keypresses per block (10-15 after every 2 repetitions of a sequence).

### 4.3 Adjustments to the Visual Statistical Learning Task

Pilot data also prompted adjustments to our original VSL paradigm. Our initial design mirrored that of Fiser and Aslin’s (2002) design, wherein there were 288 stimulus presentations

that moved across the computer screen. Our minor modifications to their paradigm followed Turk-Browne, Jungé, and Scholl (Turk-Browne et al., 2005), which included static presentation of the stimulus (important here to reduce possible confounds of oculomotor differences) and addition of a cover task, which added 24 additional stimulus presentations for a total of 312 presentations (important to promote attention given the online data collection). Using their paradigm, Fiser and Aslin reported a mean accuracy of 95% on the forced choice task across 8 participants. Turk-Browne, Jungé, and Scholl had a different paradigm, interweaving two separate streams and prompting attention to only one stream, and reported 59% accuracy. When our piloting results yielded a mean accuracy slightly below chance (mean 48.3% across 9 participants [8 TD, 1 DLD]), we modified the design to double exposure to 576 stimulus presentations (in addition to 48 repetitions to facilitate the cover task, 624 total). This slightly increased mean accuracy on the task, although group-level accuracies continued to hover between 50% and 60% for both the TD and DLD groups. See Figure 4.2 for differences in VSL accuracy between the two designs.

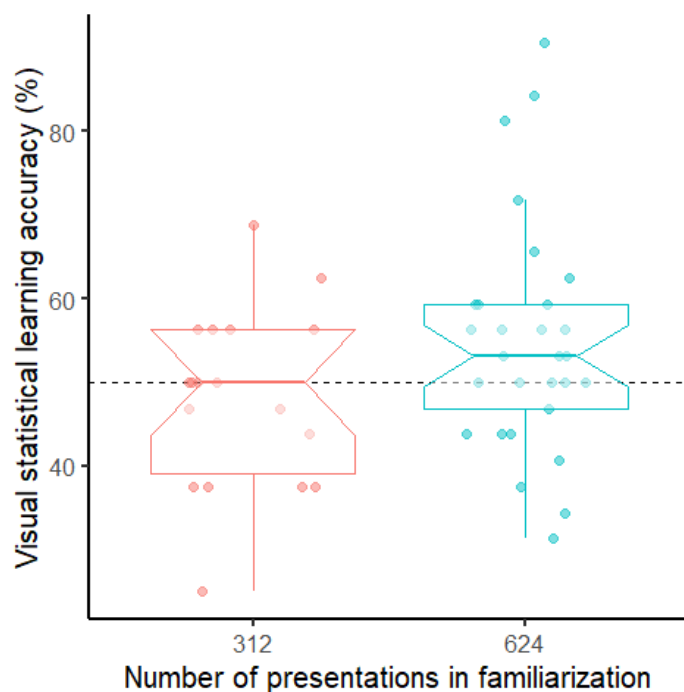


Figure 4.2 Distribution of individual accuracies two different paradigms of the VSL forced-choice task: the version with 312 stimulus presentations and the version with 624 stimulus presentations.

This relative lack of learning on the VSL may be attributed to a variety of factors. For one, varying levels of attention may have influence performance. Though some publications suggest that statistical learning is automatic or spontaneous (Fiser & Aslin, 2002; Fiser & Aslin, 2001), Turke-Brown et al. (2005) found that selective attention plays an important role in visual statistical learning. While all participants achieved at least 75% accuracy on the cover task (see Figure 4.3), it is possible that the nature of the task was too simple to promote adequate attention, particularly given that all procedures took place in the participants' home. While they were monitored over Zoom and instructed to be in a quiet space, laboratory conditions would be more consistent and have fewer distractions.

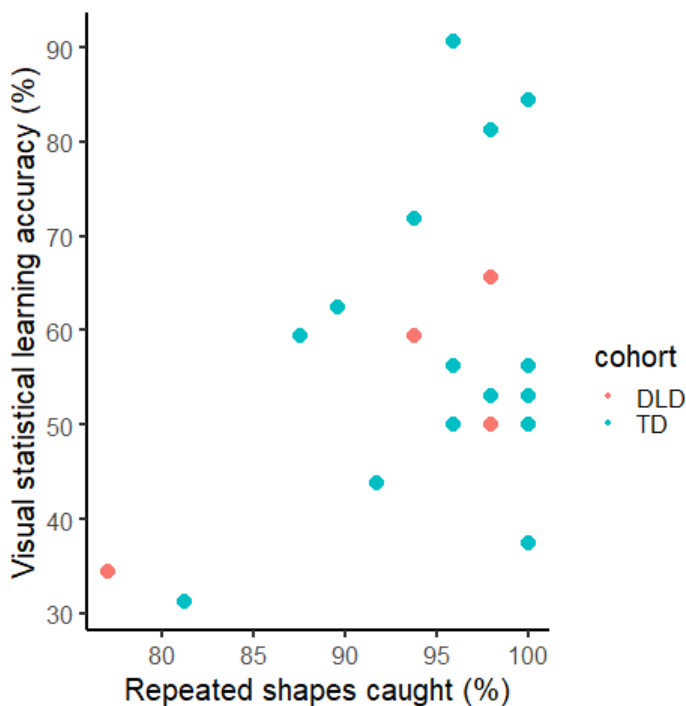


Figure 4.3 The relationship between performance on the VSL cover task (% of repeated shapes caught) and accuracy on the VSL forced choice task.

Siegelman and colleagues (2017) also reviewed challenges of a traditional VSL design. Though their publication discussed considerations for understanding individual performance on the VSL, it also highlights possible shortcomings of our own group-based design. For one,

according to Siegelman (2017), most of the sample in a VSL task is expected to perform at chance; this may suggest that we need a larger sample size to see greater learning at the group level. Additionally, in our forced choice task, we only probed one skill: identifying a “true” triplet for a foil triplet. Instead, Siegelman and colleagues (2017) suggest that more variation among test phase questions (e.g., identifying a “true” pair from a foil pair, identifying a partially “true” triplet from a foil triplet) can better capture true statistical learning.

#### *4.4 Limitations & Future Directions*

A primary limitation of our study was our limited sample size. As discussed above, an increased sample size, particularly within the DLD group, is critical for identifying trends and differences in procedural learning skill between the two groups. Our lab intends to continue to collect data using current paradigms following our initial power analysis (21 per group).

Additionally, although the scope of this study focused on the relationship between procedural (implicit) learning and manual motor demands, an avenue for further investigation is the impact of manual motor demands on explicit learning skill. In an extension of the current project discussed in this thesis, our lab has also simultaneously collected data on an explicit version of the SRTT. In this version (administered after both the implicit SRTT and VSL), participants were informed of the presence of a sequence and shown the sequence in numerical form both before the task and during sequenced keypresses. We intend to continue to collect these data in order to further examine explicit learning and manual motor demands. Greater understanding of both implicit and explicit learning profiles of persons with DLD is critical for informing improved clinical practice for this population.

A final challenge (and important aspect) of this project was the modality in which it was conducted. In advent of the COVID-19 pandemic, our project utilized completely online data

collection. Therefore, a major component of this particular study was adaption of both procedural learning paradigms and Fidler method tasks to an online format. As discussed in the above sections, much of this project entailed piloting and adjusting paradigms based on initial outcomes. Limited research exists on the translation of these specific paradigms and tasks into a virtual format, and further research is warranted to investigate the validity of these tasks in comparison to in-person administration.

Though adaptation to an online format poses challenges, we also recognize that online administration allows for the possibility of broader and more diverse recruitment, which is critical for capturing representative samples and reaching communities that are not traditionally included in research. In this way, online data collection can foster more equitable participation in research and produce better-informed outcomes.

### **Conclusions**

This study represents potential differences in sequence-based procedural learning skill between adults with developmental language disorder and typically developing adults. Although results are as yet inconclusive, it is possible that differences in sequence-based procedural learning only exist when manual motor movement is incorporated in the learning task. This potential finding would provide important insight into the patterns of deficits associated with DLD. Alternatively, should significant differences between the group's task performance be found on both sequence-based procedural learning tasks (with the typically developing group outperforming the DLD group), this would support both the Procedural Deficit Hypothesis and the Sequential Pattern Learning Deficit Hypothesis. We have also presented methods for collecting such data online and adjusting paradigms to obscure explicit knowledge of sequences and promote greater learning. In summary, further investigation is warranted to understand

sequence-based procedural learning skill and the influence of manual motor demands in adults with developmental language disorder.

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## Appendix

### Modified Token Task (MTT) Directions

*Based on Morice & McNicol, 1985 and De Renzi & Faglioni, 1978; adapted for online administration.*

1. Click the large white circle and the small green square
2. Click the small blue circle and the large yellow square
3. Click the large green square and the large red square
4. Click the large white square and the small green circle
5. Move the red circle onto the green square
6. Click the blue circle with the red square
7. Click the blue circle and the red square
8. Click the blue circle or the red square
9. Move the green square away from the yellow square
10. If there is a blue circle, click the red square
11. Move the green square next to the red circle
12. Move the squares slowly and the circles quickly
13. Move the red circle between the yellow square and the green square
14. Click all the circles, except the green one
15. Click the red circle - no - the white square
16. Instead of the white square, click the yellow circle
17. In addition to clicking the yellow circle, click the blue circle
18. Click the square that is next to the square that is below the red circle.
19. Using the circle that is above the white square, click the blue circle.
20. move the blue circle and the red circle and the white square.
21. Click the red square and the green square and move the white circle and the yellow square.
22. Click the blue circle and the white square and the green square and the red circle.
23. Click the square below the circle next to the red circle.
24. Click the red circle and the green circle and move the yellow square.
25. Before clicking the yellow circle, move the circle above the square that is next to the yellow square.
26. Move the yellow circle and the square that is below the blue circle.
27. Using the square that is below the green circle, click the red square.
28. Click the circle that is next to the circle that is above the yellow square.
29. Move the white square and the square that is below the red circle.
30. Click the red square and the green square and the white circle and the yellow square.
31. Move the yellow circle and the blue square and the white circle.
32. Click the yellow circle and the green square and move the red circle and the white square.
33. Before clicking the red square, move the square next to the square that is below the white circle.

34. Click the circle next to the circle above the blue square.
35. Move the green square and the red circle and Click the blue square.
36. Using the circle that is above the green square, Click the blue square.
37. Click the square next to the square below the green circle.
38. Click the square that is below the circle that is next to the green circle.
39. Move the yellow circle and the blue square and Click the white circle.
40. Move the green square and the circle that is above the yellow square.
41. Click the blue square and the white square and move the green circle and the red square.
42. Click the green circle and the white circle and the red square and the yellow circle.
43. Move the white square and the yellow square and the blue circle.
44. Before clicking the blue square, move the circle next to the circle that is above the yellow square.

Instructions were recorded by a female speaker with a standard American dialect and given virtually. No repetitions were allowed. Responses were judged as correct or incorrect to produce a raw score (maximum of 44).

### Spelling Words

*From Fidler et al., 2011.*

1. Realtor
2. Trailer
3. Tiresome
4. Miracle
5. Conscience
6. Bouquet
7. Carriage
8. Predominately
9. Accommodation
10. Immortalize
11. Necessitate
12. Cupboard
13. Peculiar
14. Faucet
15. Analysis

Items were recorded by a female speaker with a standard American dialect and given virtually. Each item was presented as the single word, followed by the word in a sentence, followed by an additional repetition of a single word. No further repetitions were allowed. Spelling was judged as correct or incorrect to produce a raw score (maximum of 15).

Clinical Evaluation of Language Fundamentals, Fourth Edition Word Definitions Subtest (CELF-4 WD)

*From Semel et al., 2003. Not included due to copyright law.*

Administered and scored according to publisher guidelines. Standard scores obtained based on age norms or 21-year old norms for anyone of that age or older.

Scoring Procedures

*From Fidler et al., 2011.*

Raw scores (from the MTT and Spelling Test) and a standard score (from the CELF-4 WD) were plugged into the following formula to determine group membership:

$$\text{Group Membership} = 6.7110 + (-0.1698 \times \text{Spelling Raw Score}) + (-0.1151 \times \text{CELF-4 WD Standard Score}) + (-0.1107 \times \text{MTT Raw Score})$$

A positive value indicates membership in the DLD group. A negative value indicates membership in the TD group.