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Implicit and Explicit Sequence Learning in Adults With Developmental Language Disorder

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ABSTRACT

Purpose: Developmental language disorder (DLD) is a neurodevelopmental disorder that impacts approximately 7% of the population and is characterized by unexplained deficits in expressive and/or receptive components of language. A common procedural learning task, serial reaction time (SRT), has been used to develop models of the basis of DLD. However, paradigms involve differing levels of implicit and explicit learning during this task, muddying interpretations of the data. Here, we tested adults with DLD on implicit and explicit SRT tasks to better understand implicit and explicit procedural learning in this population. We hypothesized that adults with DLD would demonstrate reduced learning on only the implicit SRT task, as alternate explicit neural mechanisms could lead to equivalent performance on the explicit task.
Method: Fifty participants (25 with DLD and 25 with typical language) completed implicit and explicit SRT tasks, measuring their ability to learn visually presented 10-element sequences. Group differences were evaluated on sequence learning, error rates, and explicit recall of the sequence after learning.
Results: Sequence learning was the same between the groups on both tasks. However, individuals with DLD showed increased errors and significantly worse recall of the explicitly learned sequence.
Conclusions: Results suggest that sequence learning may be intact in this population, while aspects of explicit learning and motoric responses are impaired. Results are interpreted in light of a neurobiological model of DLD.
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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 nonverbal IQ, or a lack of access to language in one's environment (Bishop et al., 2017). Language deficits and associated challenges often persist into adolescence and adulthood (Clegg et al., 2005; Del Tufo & Earle, 2020). Adults with DLD also experience adverse psychosocial outcomes, such as poorer friendship quality and increased risk of psychiatric disorders, as well as reduced educational achievement and employment (Clegg et al., 2005; Conti-Ramsden & Botting, 2008; Conti-Ramsden et al., 2018; Durkin et al., 2012; Law et al., 2009).

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A prominent theory of the neurobiological basis of DLD, the procedural (circuit) deficit hypothesis, suggests that individuals with DLD have difficulties in procedural learning and memory (Ullman et al., 2020). Much of the theoretical basis for this model of DLD is based on behavioral performance of children with DLD on the serial reaction time (SRT) task (Nissen & Bullemer, 1987). However, specifics of this paradigm may affect the interpretation of the results. In this study, we examined sequence learning in adults with DLD to determine whether such deficits persist into adulthood, and we manipulated aspects of the SRT learning paradigm to determine the differential effects of implicit and explicit learning in this population.

SRT Tasks

Since it was first introduced in 1987, the SRT paradigm has been used across many fields, including motor learning, cognitive neuroscience, psychology, and communication sciences and disorders (Dienes & Perner, 1999; Krakauer et al., 2019; Nissen & Bullemer, 1987). In a typical SRT paradigm, a participant responds to a (typically visual) cue with an associated button press as quickly as possible (e.g., when the leftmost light appears, hit the leftmost button; see Figure 1). In some blocks of stimuli, the order of targets is in a repeated sequence, which allows participants to learn the order via practice. Sequence learning (or sometimes conceptualized as motor learning or implicit learning, depending on the field) is quantified by calculating the difference in response time between sequenced blocks and random blocks, such that reduced response times indicate that motor and/or sequence learning has occurred (Krakauer et al., 2019; Robertson, 2007). The sequence to be learned can vary across several dimensions, including length (five-item, 10-item) and whether the sequence is fixed/deterministic (i.e., always in the same order) or probabilistic (e.g., one will be followed by three 85% of the time and by two 15% of the time), or whether the participant is instructed on the existence of a sequence, which is thought to impact how implicit or explicit the learning may be.

In this study, we manipulated this last variable (implicit vs. explicit learning) by testing participants on implicit and explicit SRT tasks. Most of the SRT tasks in the DLD literature are intended or assumed to be implicit. The implicitness/explicitness of the memory leads to associated assumptions about underlying neural substrates that might be recruited.

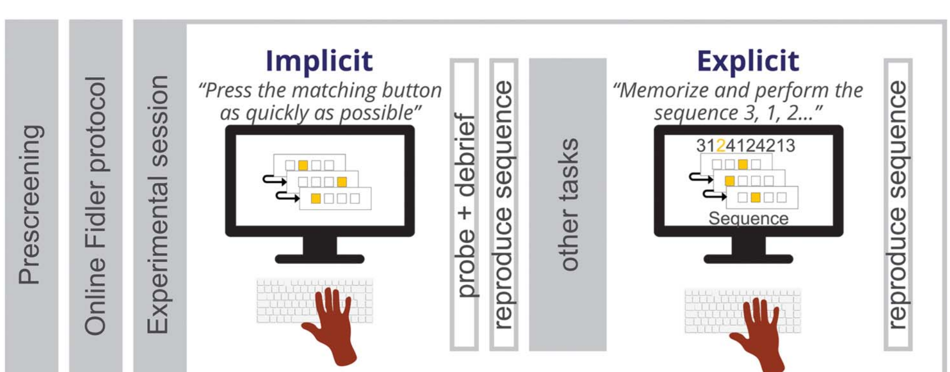
Differentiating Implicit/Explicit Versus Procedural/Declarative

SRT tasks are often considered implicit and taken as evidence for procedural learning deficits in DLD (Ullman & Pierpont, 2005). However, implicit/explicit and procedural/declarative dichotomies are not synonymous, though some fields may use these terms interchangeably, depending on the paradigm and exact construct being studied (Dienes & Perner, 1999). Here, however, we consider these separate constructs that may rely on different neural substrates and are manipulated separately in this study. It is therefore necessary to briefly discuss these frequently conflated concepts.

Procedural memory refers to procedures, skills, and habits that one demonstrates by doing (sometimes called "knowing how" to do something), while declarative memory refers to knowledge of facts and personal experiences (sometimes called "knowing that"; Cohen & Squire, 1980). A common confusion is between procedural/declarative and implicit/explicit memory. Implicit memory is that which is unable to be expressed verbally or is hidden from conscious awareness, whereas explicit memory can be expressed verbally and is available to conscious awareness (Dienes & Perner, 1999; Graf & Schacter, 1985). "Learning" can also be implicit or explicit: Implicit learning is that which is done without trying or conscious awareness; explicit learning is intentional and conscious. Note also that the difference between tasks that tax (procedural) learning versus memory systems are not particularly clear, as deficits in acquisition and retrieval cannot always be easily differentiated.

There is a relationship between implicit/explicit and procedural/declarative, as much procedural memory is accessed implicitly (e.g., one cannot verbalize how to ride a bicycle but must perform the action to demonstrate learning), and much declarative memory is accessed explicitly (e.g., I must intentionally and consciously recall the state capitals). However, these concepts are not identical, and memory can move from implicit to explicit. It

Figure 1. Experimental protocol. Potential participants completed online prescreening, where they described their language background and disclosed exclusions (e.g., history of head trauma). If eligible, they met with a researcher on Zoom for approximately 30 min to complete the online Fidler protocol. Participants further recruited for the study in this article then completed an experimental session, in which they completed an implicit SRT task, several other tasks, and then an explicit SRT task. SRT = serial reaction time.



has been argued that *learning* most motor and cognitive skills involves explicit components (Henke, 2010; Krakauer et al., 2019). In fact, the dichotomy between procedural/declarative arose in the amnesic patient HM, who was able to improve on procedural tasks (mirror drawing) despite having no declarative memory of learning it. However, learning in HM's case was indeed explicit, as he was instructed on how to perform the task each day, which is consistent with other reports of learning in amnesia (Roy & Park, 2010; Stanley & Krakauer, 2013). This blurring of implicit/explicit and procedural/declarative (and learning vs. memory) can make interpretation of results difficult.

Here, we consider the SRT task a procedural learning task (it is a skill that you learn by doing and demonstrate by performing; Dienes & Perner, 1999; Krakauer et al., 2019; Robertson, 2007), but both the learning and memory of that SRT sequence can be more or less explicit. Electrophysiological evidence suggests that the neural substrates used while learning an SRT sequence change as participants become explicitly aware of the sequence (e.g., Lu et al., 2023; Zhuang et al., 1997). In this study, we manipulate the learning of the sequence in implicit and explicit versions of the task and measure the explicitness of the knowledge acquired.

Implicit and Explicit SRT Tasks

Implicitness/explicitness of learning and retrieval during an SRT task is often manipulated by giving or not giving participants instructions or by adding a distractor task. Explicit awareness of the sequence is typically assessed after the task by informing the participant that there was a sequence and asking them to generate it. Even without being explicitly informed of the sequence, participants may slowly become aware of the existence of a repeating pattern during learning and begin to use both implicit and explicit mechanisms for learning it (Lu et al., 2023; Zhuang et al., 1997). Indeed, the original SRT study showed that under single-task conditions, 11 out of 11 participants queried noticed the sequence (Nissen & Bullemer, 1987). Variables other than instruction also impact explicit learning of "implicit" (uninstructed) SRT tasks: Explicit learning in an "implicit" task is increased when sequences are short and/or deterministic (Stefaniak et al., 2008).

Behavioral Performance on Explicit and Implicit SRT Tasks

Some studies have contrasted behavioral performance on explicit and implicit SRT tasks directly to determine if similar or different mechanisms are used. A study focused on Parkinson's disease showed that participants were impaired on both implicit and explicit SRT tasks, indicating that the striatum is also involved in explicit SRT tasks (Wilkinson et al., 2009). Two studies in dyslexia found deficits in implicit but not explicit sequence learning (Jiménez-Fernández et al., 2011; Vicari et al., 2003) as well as increased errors during the implicit SRT task in the group with dyslexia (Vicari et al., 2003). One study in dyslexia found no differences in implicit learning after accounting for attentional differences and overall (motor) slowness; they found deficits in explicit sequence learning characterized by reduced explicit knowledge after learning (Staels & Van den Broeck, 2017).

Neural Constructs Used For Explicit and Implicit SRT Tasks

As demonstrated by these behavioral differences, implicit and explicit learning during SRT tasks may result in the recruitment of different neural substrates. A recent meta-analysis of the neural basis of SRT task learning in neurotypical adults found that, as anticipated, implicit and explicit SRTs activate the striatum (Janacsek et al., 2020); the authors specifically focused on activation differences in sequence versus random blocks in order to account for other cognitive and motor factors that might be recruited in all blocks of training. When instead just comparing sequence learning to rest, cerebellar and premotor cortical regions were also recruited. This study was not powered to find differences specifically between neural correlates of implicit and explicit SRT tasks. An earlier meta-analysis did contrast the two types of SRT tasks (without accounting for sequence > random), which found consistent activation in cortical regions and rostral thalamus in explicit SRT tasks, with more consistent activation in more caudal regions of the thalamus and the right cerebellum in implicit SRT tasks (Hardwick et al., 2013). Given the converging evidence for striatal deficits in DLD (Krishnan et al., 2022; Ullman et al., 2024), modulating the implicitness/explicitness of the SRT task may allow for a better behavioral picture of DLD in adulthood that would suggest important areas of research into the neural correlates of DLD.

Implicit/Explicit SRT Tasks and DLD

The procedural (circuit) deficit hypothesis posits that individuals with DLD demonstrate deficits in procedural memory that underlies their language difficulties (Ullman & Pierpont, 2005)—regardless of implicitness or explicitness of learning. Confirmatory evidence is found in deficits in (putatively implicit) SRT performance and perceptual sequence learning in DLD (Evans et al., 2009; Lum et al., 2014; Ullman et al., 2020). Consistent neural evidence for this model suggests that the structure of the caudate nucleus (part of the striatum in the basal ganglia) is altered in DLD (Badcock et al., 2012; Cler et al., 2020; Herbert et al., 2003; Krishnan et al., 2022; Ullman et al., 2024). Contradictory evidence suggests that individuals with DLD do not struggle with all procedural learning and can struggle with declarative learning (e.g., list learning; Bishop & Hsu, 2015; Gerken et al., 2021; Hsu & Bishop, 2014; Jackson et al., 2020; Mayor-Dubois et al., 2014), and it is unknown whether this model would hold in adulthood.

The authors of a meta-analysis on SRT tasks in DLD (containing eight studies, all regarded as implicit because no instructions were given) noted that group differences were smaller/nonexistent with older participants. They hypothesized that older participants could compensate for faulty procedural learning systems with declarative systems that are not yet fully developed in younger participants (Lum et al., 2014; Ullman & Pullman, 2015); the meta-analyses of neural activations do not hold with this view, as medial temporal regions do not appear to be recruited for SRTs in neurotypical learners (Hardwick et al., 2013; Janacsek et al., 2020). Still, it is possible that adults with DLD would recruit these substrates nonetheless, or they could rely on other putatively unimpaired mechanisms (cortical premotor regions, cerebellum). A recent study in adults with DLD indicated a small but significant deficit in (implicit) SRT learning of 10-item sequences (Earle & Ullman, 2021), with impaired declarative retrieval after consolidation. Behavioral results from implicit and explicit SRT tasks could suggest an updated neurobiological model of DLD in adulthood to be tested empirically with measures of brain structure and function in the future.

Research Question and Hypotheses

In this study, adults with DLD completed implicit and explicit versions of the SRT paradigm to characterize procedural learning and help develop models of neural correlates of DLD in adulthood. Based on converging evidence of striatal deficits in DLD (Ullman et al., 2024) and the importance of striatal activation in implicit SRT learning (Janacsek et al., 2020), we hypothesized that the DLD group would have markedly worse performance than the typical development (TD) group on the implicit SRT. We were unsure but interested in what would happen behaviorally in the explicit SRT. From a neural perspective, it is possible that the increased reliance on putatively in-tact cortical (premotor) or cerebellar mechanisms may lead to better performance on the explicit than implicit task for the DLD group (Hardwick et al., 2013); perhaps they could recruit in-tact medial temporal lobe processing (per Lum et al., 2014; Ullman & Pullman, 2015) that neurotypical participants are not using (Hardwick et al., 2013; Janacsek et al., 2020). Our overall research goal was to delineate explicit and implicit aspects of SRT learning that could point to underlying neural mechanisms to be probed further.

Method

Participants

Fifty participants were included in the final analyses. All participants were native English speakers who reported acquiring English below the age of 2 years. Participants were between the ages of 18 and 35 years. Due to the COVID-19 pandemic, all data collection took place online. Participants were compensated for their time. All participants provided informed consent as approved by the University of Washington Institutional Review Board.

Operationalizing DLD

Awareness of DLD remains low compared to other neurodevelopmental disorders (attention-deficit/hyperactivity disorder, autism spectrum disorder), and as such, adults with developmental language difficulties are likely to have one of a variety of diagnoses from childhood or, frequently, no diagnosis. This makes recruitment difficult. Participants were recruited broadly, without specific mention of language difficulties, and then screened over Zoom using the Fidler protocol (Fidler et al., 2011) modified for online assessment. Participants who met criteria for DLD were included in the study. A subset of participants who met criteria for typical language were selected for participation to match the DLD group in age, gender, and schooling.

The Fidler protocol is a commonly used tool to identify adults with DLD (Fidler et al., 2011). In the Fidler protocol, an equation using two tasks ($6.5727 – 0.2184 \times \text{spelling} - 0.1298 \times \text{token}$) was shown to identify participants with a history of receiving speech-language services with a sensitivity of 80% and specificity of 87% (Fidler et al., 2011, erratum). The tasks were the 44-item modified token test in which participants follow verbal directions (De Renzi & Faglioni, 1978; Morice & McNicol, 1985) and a 15-word spelling test.

Here, the Fidler protocol was modified for online testing. For the spelling test, words were prerecorded as [word] [word in sentence] [word], and participants listened to the samples over headphones. Participants would then write the word on a piece of paper and hold it up to the webcam for live scoring by a researcher. The modified token test was adjusted to be performed online using Pavlovia.org (Bridges et al., 2020) to present the test stimuli in the same format as the in-person test. As with the in-person version, participants were presented with circles and squares of varying colors and sizes and heard prerecorded instructions. The instructions were modified from, for example, “Touch the large white circle and the small green square” in the original test to “Click the large white circle and the small green square" for the online adaptation. Performance was scored as correct or incorrect by a researcher. All tasks were recorded for later rechecking as needed.

Finally, the Fidler paper states that none of the individuals in the original study showed frank reading disability (Fidler et al., 2011); however, difficulty with spelling is also indicative of dyslexia, and a participant could theoretically do so poorly on the spelling task alone to be assigned to the DLD group. As we were focused on DLD (with or without dyslexia), we excluded one additional participant who had difficulty with only the spelling task but performed well on the "following directions" test (> 40/44). The remainder of the participants thus had at least five errors on following auditory directions with varied errors in the spelling task, indicating an underlying difficulty with language processing in addition to possible dyslexia.

Experimental Protocol

Our full experimental protocol is schematized in Figure 1. Participants completed the prescreening offline and the Fidler protocol online. Then, they completed an experimental session online: the implicit SRT task, other distractor tasks, and then the explicit SRT task. The tasks were not counterbalanced, as having the explicit task first would necessarily alert the participant to a likely sequence in the implicit task.

The SRT tasks were specifically modeled after Lammertink et al. (2020), which was modified from Lum and Kidd (2012) and ultimately from Nissen and Bullemer (1987). Protocols were programmed on http://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 squares turned yellow (see Figure 1). They were instructed to, for example, press the leftmost key with their leftmost finger when the leftmost box turned yellow. To prevent participants from intentionally selecting incorrect responses simply to finish the task more quickly, the next stimulus was not presented until the correct button was pressed. An interstimulus interval of 250 ms occurred between selection of the correct button and presentation of the next stimulus.

Participants first completed 16 pseudorandom button presses to make sure they understood the paradigm and had no further questions (data not analyzed). Consistent with the Lammertink paradigm, each participant then 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 a 10-element sequence. Two sequences were used (3412413421, Clark & Lum, 2017; 4231243143, Lammertink et al., 2020), and the order of the sequences (one for implicit SRT, one for explicit SRT) was counterbalanced.[1] In a variation from the Lammertink paradigm, the sequence blocks also incorporated an additional 10–15 pseudorandom keypresses after every two sequence repetitions (or every 20 keypresses) in order to deter explicit knowledge of the presence of a sequence. The response times on these keypresses were not analyzed for the purposes of this study.

Implicit SRT Task

Participants were asked to respond to each stimulus with a button press as quickly and accurately as possible. They were not given any information about a consistent order, sequence, or pattern to learn. Following the implicit SRT task, participants were probed for explicit knowledge of the sequence (Desmottes et al., 2016). Participants were asked, "Did you notice anything in particular about any of the keypresses?" and prompted further if needed for any explicit awareness. Then, participants were told that the keypresses had been in a sequence and were instructed to recreate the sequence. They were given 30 keypresses to try to reproduce the sequence.

Explicit SRT Task

After several intervening tasks (not reported here), participants completed an explicit SRT paradigm designed to closely match the implicit SRT paradigm. To promote explicit learning, the presence of the sequence and the sequence itself were disclosed to the participants prior to the start of the task. Participants were exposed to the written sequence for 2 min and told to memorize it. They were then asked to repeat the sequence aloud and, if needed, were given a second opportunity to view the sequence. The SRT task then proceeded as before, with instructions to press the corresponding buttons as quickly and accurately as possible. During this explicit SRT portion, a written representation of the sequence and boxes corresponding to the finger presses were highlighted, with the next number changing color with the box (see Figure 1). It also said "sequence" or "random" below the boxes, depending on the block. After completing this SRT task, participants were again given 30 keypresses to try to reproduce the sequence.

Statistical Analyses

Data cleaning and analysis were performed in R (Version 4.3.2). For each task, motor learning, the number

[1]The order of the SRT tasks, implicit and explicit, were not able to be counterbalanced, as informing participants of the sequence in the explicit task first would necessarily make them aware of the sequence in the implicit task. Therefore, it was always implicit and then explicit tasks, as shown in Figure 1.

of errors, and sequence generation (recall) after learning were calculated for each participant.

Motor Learning Index

The primary measure of interest on the SRT tasks was the motor learning index, calculated as the difference in median response time between the final random block (Block 6) and final sequence block (Block 7).[2] Medians were used as they are less sensitive to outliers than means. Before calculating, incorrect keypresses were removed, as were correct keypresses that were ±3 *SD* from each participant's mean response time. A linear mixed model of the form motorLearningIdx ~ group (DLD/TD) + task (implicit/explicit) + group × task + (1|participant), with participant as a random factor, was initially used to evaluate group differences on motor learning indices. As the random factor led to a singular fit (i.e., the effect of participant neared zero, indicating that individual performance on learning on the implicit task was not correlated with performance on the explicit task), the final analysis was a linear model without mixed term of the form motorLearningIdx ~ group (DLD/TD) + task (implicit/explicit) + group × task. To verify that participants learned the sequences at all, paired *t* tests were evaluated for both the explicit and implicit tasks between the blocks used to calculate the motor learning index—Block 6 (random) and Block 7 (sequence).

Although an a priori power analysis using GPower determined that with at least 42 participants (21 DLD and 21 TD) and a power of .8 and an α of .05, large effect sizes (Cohen's $d = 0.8$) would be detected between the groups, null results were further evaluated with a Bayesian analysis to ensure results were not due to lack of power (Dienes, 2014). A Bayes analyses (R package BayesFactor) was used in which a full linear model of the same form as above (motorLearningIdx ~ group (DLD/TD) + task (implicit/explicit) + group × task + (1|participant)) was evaluated against a null model that did not include group as a factor (motorLearningIdx ~ task (implicit/explicit) + (1|participant)). If the resultant Bayes factor is above 3, that would serve as evidence that the alternative hypothesis is 3 times as likely as the null hypothesis (i.e., substantial evidence that group is an important predictor). If the resultant Bayes factor is below 0.33, that is substantial support for the null hypothesis being likelier (group is not an important predictor). Bayes factors between 0.33 and 3 suggest that the data were insensitive and unable to answer the question in its current form.

Errors

Only correct keypresses were used to calculate the motor learning index. The number of errors were compared between groups with a generalized linear model with a Poisson distribution of the form errorCount ~ group (DLD/TD) + block (1–7) + task (implicit/explicit) + all interactions, with participant as a random intercept.

Sequence Generation/Recall

To evaluate explicit awareness of sequence after sequence learning, the Levenshtein string distance (Levenshtein, 1966) between the correct sequence (e.g., 4231243143) and each set of 10 sequential items produced by the participant was calculated. The Levenshtein distance shows how similar two sequences are to each other, considering substitutions, deletions, and insertions. A small distance indicates higher similarity, with zero indicating that the sequence was reproduced completely correctly. For example, if a target was 4231243143 and the participant produced 12341234**4231243143**1234123412341234, the Levenshtein distance was calculated between the target and the first 10 digits, then between the target and digits 2–11, then the target and digits 3–12, and so on. Each participant's distance was set to the minimum of all of these; in this example, digits 9–18 were exactly the target, so the distance was zero. We evaluated group differences in the minimum Levenshtein distance statistically with Mann–Whitney *U* tests.

Results

Fifty participants completed the online data collection protocol while being supervised by a researcher over Zoom. Participant data are shown in Table 1. Groups were well matched in terms of age (18–35 years), gender, and college attendance (all but one participant in each group attended college).

Motor Learning Index

Motor learning was operationalized as the difference in mean response time of correct button presses during the final random block minus the final sequence block, in which larger differences represent more motor learning (Lammertink et al., 2020). Results are displayed

[2]Learning on SRT tasks is typically captured in this way, as the "sequence-random" difference, which we have replicated here. Some studies compare between groups only after learning (without a random block to contrast) or at least present raw (individual or group) reaction times as a measure of interest. This is nonideal for DLD, as these raw times do not account for inherent motor slowness that has also been reported. In addition, however, completing reaction time studies using the participants' own equipment means that while within-participant measurements are reliable (such that we can indeed measure a learning index by subtracting random minus sequence), between-participants measurements (like the mean of the random block for each participant) represent both their own inherent reaction time and the individual lag of their setup, making any interpretations impossible.

Table 1. Participant characteristics.

Variable	Typical language	DLD
n	25	25
Age	Range: 18–35 years Median: 21	Range: 18–35 years Median: 20
Gender	Woman: 19 Man: 5 Nonbinary: 1	Woman: 19 Man: 6
Fidler score negative = TD, positive = DLD	Range: −1.93 to −0.42 Mean: −1.30	Range: 0.15–2.0 Mean: 0.75
Attend(ed) college	24/25	24/25

Note. DLD = developmental language disorder; TD = typical development.

Table 2. Statistical results for linear model evaluating the effect of cohort and task on motor learning index.

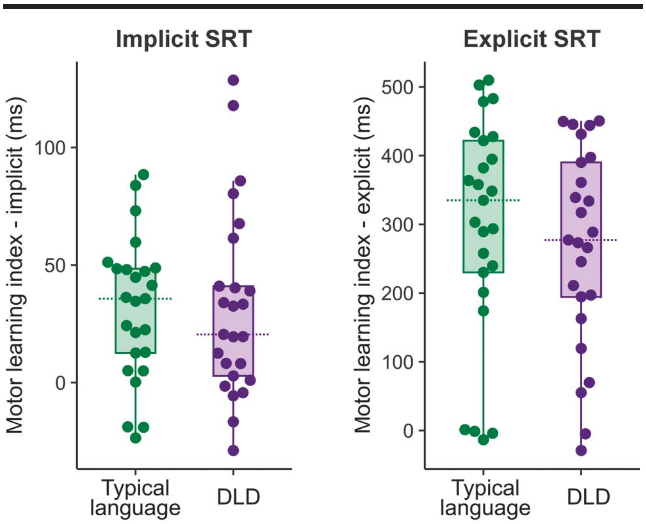
	Motor learning index (ms)			
Predictors	Estimates	CI	Statistic	*p*
(Intercept)	299.07	[255, 343]	13.51	**< .001**
Cohort [DLD]	−30.63	[−93, 32]	−0.98	.330
Task [explicit]	−267.34	[−329, −205]	−8.54	**< .001**
Cohort × Task	29.54	[−58, 117]	0.67	.506
Observations	100			
R^2/R^2 adjusted	.577/.564			

Note. Values in bold indicate significant differences (p < .05). CI = confidence interval; DLD = developmental language disorder.

graphically in Figure 2. A linear mixed model including participant as a random factor had a singular fit (i.e., the effect of participant neared 0, indicating that individual performance on learning on the implicit task was not correlated with performance on the explicit task). Therefore, a linear model without the within-participant term revealed the same results. As expected, there was a main effect of task, in which learning was increased during the explicit SRT task versus the implicit SRT task: estimate = 267, t statistic = 8.5, confidence interval (CI) [205, 329], p < .001. There were no main or interaction effects of group on the motor learning indices (see Table 2).

To verify that participants learned the sequence at all, as not learning the sequence would also lead to no group differences, paired t tests were evaluated for implicit and explicit tasks, comparing performance on the final random block (Block 6) to performance on the final sequence block (Block 7). For the implicit task, performance was significantly faster on the sequence block (mean difference = 31 ms, CI [22, 41], t = 6.5, p < .0001). For the explicit task, performance was also significantly faster on the sequence block (mean difference = 284 ms, CI [241, 327], t = 13.2, p < .0001). Bayesian analysis was used to determine whether there was good evidence for the null hypothesis, or whether the data were insensitive to the contrast of interest (group). Comparing a full model with group to a model without group resulted in substantial evidence for the null hypothesis with a Bayes factor of 0.1 (criterion: < 0.33 means evidence for null, > 3.0 means evidence against null; 0.33–3.0 means data are insensitive to contrast and more data should be collected; Dienes, 2014). Thus, our data can be said to provide substantial evidence of performance being the same between groups, rather than that we do not have enough evidence to determine if there is a difference.

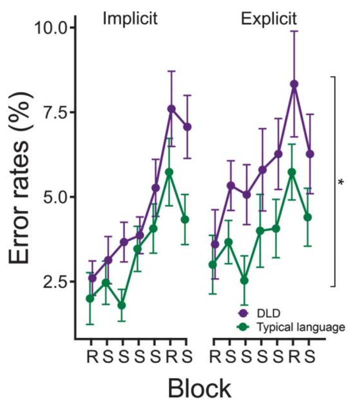
Figure 2. Motor learning index (difference between final random block and final sequence block) for the implicit SRT (left) and explicit SRT (right) tasks. In each plot, participants with typical language are shown on left, and the DLD group is shown on right. Group median is shown with dotted line. SRT = serial reaction time; DLD = developmental language disorder.



Errors

Figure 3 shows mean errors per group. Visually, the TD group made fewer errors than the DLD group throughout the tasks. Note that for visualization purposes, counts were expressed as error rate (errors made/keypresses in the block) because the first two random blocks had only 20 keypresses, while the rest were 60 keypresses. Statistically, there were significant main effects of block (estimate = 0.16, CI [0.11, 0.21], t = 6.07, p < .001), task (estimate = −0.45, CI [−0.85, −0.06]), and cohort (estimate = 0.49, CI [0.005, 0.97], t = 1.99, p < .05; see Table 3), but no significant interactions. Errors gradually increased throughout the experiment (0.16 additional errors per subsequent block). Group membership in the DLD group increased the error count by around 0.44 regardless of block.

Figure 3. Error rates are shown as mean ± standard error. Results from implicit SRT task are shown on the left; results from explicit SRT task are shown on the right. Blocks are labeled R for random and S for sequence. Asterisk indicates significant main effect of group, with additional main effects of block and task but no significant interactions with group. SRT = serial reaction time; DLD = developmental language disorder.



Explicit Knowledge—Report and Sequence Reproduction

Implicit Task

Following the implicit SRT task, participants were interviewed to see if they had noticed anything about the keypresses. Forty percent of the typical language group reported noticing a sequence or pattern; 32% of the DLD group reported noticing a sequence or pattern.

Participants were then informed there was a sequence and asked to recreate it. They were given 30 keypresses to recreate the 10-item sequence. Figure 4A shows the Levenshtein minimum string distance between the "best" sequence the participant produced and the target sequence (left: following implicit task; right: following explicit task). Mann–Whitney *U*/Wilcoxon rank-sum tests were used to test group differences. There were no group differences on sequence reproduction following the implicit SRT task (estimate = 0, CI [0, 1], $W = 337$, $p < .62$).

Explicit Task

Following the explicit SRT task, participants were again asked to recreate the sequence they had just learned. The DLD group reproduced the sequences significantly worse than the typical language group (estimate = 0, CI [0, 2], $W = 217$, $p < .022$).

In order to explore whether sequence performance was related to a deficit in verbal recall of the sequence, Figure 4B shows whether participants correctly recited the sequence after 2 min of study before the explicit SRT task, compared to the Levenshtein distance of their best sequence recreation following training on the explicit sequence. The same number of participants in each group correctly recited the sequence before doing the SRT task. Note that many participants in the DLD group who correctly recited the sequence nonetheless failed to recreate it accurately after training.

Discussion

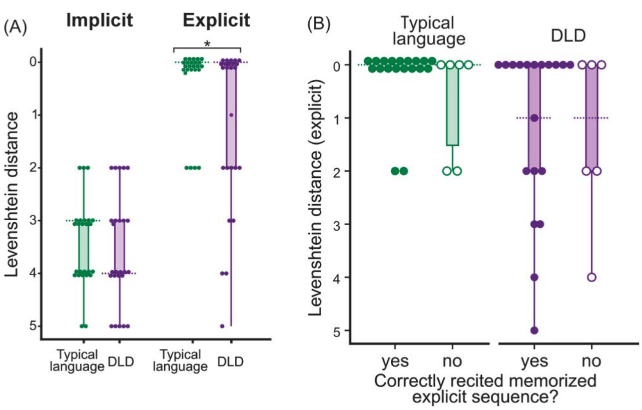
The primary aim of this study was to examine procedural learning in adults with DLD by measuring

Table 3. Statistical results for generalized linear mixed model evaluating the effect of cohort and block on error counts with Poisson distribution.

Predictors	Number of errors per block			
	Estimate	**CI**	**Statistic**	***p***
(Intercept)	−0.11	[−0.47, 0.25]	−0.60	.549
Cohort [DLD]	0.49	[0.005, 0.97]	1.99	**.046**
Block	0.16	[0.11, 0.21]	6.07	**< .001**
Task [implicit]	−0.45	[−0.85, −0.06]	−2.26	**.024**
Cohort × Block	−0.01	[−0.08, 0.06]	−0.31	.758
Cohort × Task	−0.19	[−0.70, 0.32]	−0.73	.466
Block × Task	0.07	[−0.01, 0.15]	1.79	.074
Cohort × Block × Task	0.02	[−0.08, 0.12]	0.47	.638
	Random effects			
σ^2	0.40			
$\tau_{00\ subjID}$	0.38			
ICC	.49			
N_{subjID}	50			
Observations	700			
Marginal R^2/conditional R^2	.214/.600			

Note. Values in bold indicate significant differences ($p < .05$). CI = confidence interval; ICC = intraclass correlation coefficient.

Figure 4. (A) Explicit recall and performance of 10 item sequences (Levenshtein distance) following implicit (left) and explicit (right) tasks. Measured as the distance (number of insertions, deletions, substitutions) between the target and the closest reproduction of the sequence. (B) Explicit recall and performance (Levenshtein distance) by cohort and whether participants correctly recited the sequence before SRT learning and performance. Medians are shown in dotted lines. SRT = serial reaction time; DLD = developmental language disorder.



performance on SRT tasks that involved more implicit or explicit learning. We hypothesized that, consistent with proposed deficits in the striatum, participants with DLD would show less learning on the implicit SRT task, which relies more heavily on the head of the left caudate (Hardwick et al., 2013). We hypothesized that performance on the explicit SRT may be equivalent between the groups, if participants with DLD could rely on mechanisms likelier to be recruited for explicit SRT tasks (Hardwick et al., 2013). Instead, we found that participants with DLD showed equivalent sequence learning to those with typical language on both the implicit and explicit SRT tasks (i.e., there was strong evidence for the null hypothesis per the Bayesian analysis). We found that participants with DLD produced more errors and were less able to recreate the explicitly learned sequence than the cohort with typical language.

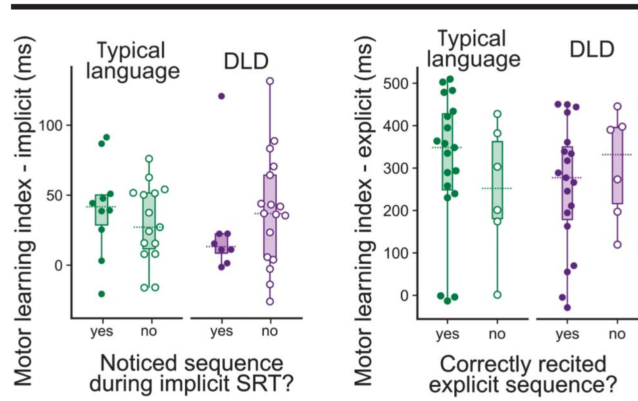
Our results are most similar to a recent study in dyslexia, in which response times were equivalent between the groups, but explicit sequence learning was impaired in terms of reduced explicit knowledge after learning (Staels & Van den Broeck, 2017). This is in contrast to some studies in children (Lum et al., 2014) and adults (Earle & Ullman, 2021), with DLD utilizing only implicit SRT tasks, in which learning is impaired. Of note, a meta-analysis of SRT tasks in DLD did find studies with no group differences, particularly those with older ages or with extended training on the SRT sequence; authors suggest that this could be due to increased availability of declarative mechanisms that are still developing in younger participants (Lum et al., 2014; Ullman & Pullman, 2015).

Explicit Awareness Differentially Impacting Sequence Learning in DLD?

In the implicit task (see Figure 5A), there appears to be a trend showing that participants with typical language who reduce their reaction times more (i.e., learn the sequence better) are likelier to report having noticed a sequence during the task. This suggests that either they are becoming aware of the sequence partway through and then using that awareness to learn the sequence better or perhaps improved implicit learning brings the sequence to their attention somehow to transfer that implicit learning into explicit knowledge. Interestingly, the participants with DLD showed the opposite pattern, such that those who reported noticing a sequence were among those who learned the least.

Similarly, explicit knowledge during the explicit task seemed to differentially relate to sequence learning in DLD. Participants were given 2 min to study and memorize the sequence in the explicit task. They were asked to recite it, and if they were incorrect, they were asked to study it again. The sequence was also displayed on the screen during the task to reduce working memory load. Figure 5B shows the motor learning index during the explicit task compared to whether the participant successfully recited the sequence before that task. Again, it appears as though the typical language group benefitted from explicit knowledge, and the DLD group who did memorize the sequence learned less than those who did not. These findings are exploratory (and the causal direction is unclear) but again contribute to our findings that it is, in fact, explicit learning that appears to be different in these adults with DLD. This also suggests that in a typical

Figure 5. (A) Motor learning in the implicit task, grouped by cohort (typical language, DLD) and whether the participant indicated noticing a sequence following the implicit SRT task (yes, no). (B) Motor learning in the explicit task, grouped by cohort and whether the participant correctly recalled the written explicit sequence following 2 min of study. SRT = serial reaction time; DLD = developmental language disorder.



"implicit" SRT task (without interstitial masking keypresses) in which most participants are gaining explicit knowledge, recruiting explicit learning mechanisms could differentially improve performance of the participants with typical language while actually reducing the performance of those with DLD.

Non–Sequence Learning Differences

In this study, we did not find evidence of an implicit learning deficit in adults with DLD measured by response times on an implicit SRT task that used additional masking keypresses to discourage explicit learning. Although contrary to Earle and Ullman (2021), who employed a typical implicit SRT task (i.e., without masking keypresses), our findings may still be in line with a meta-analysis in DLD showing smaller group differences in studies with older participants (Lum et al., 2014). We further showed no sequence learning differences as measured by response time differences between sequence and random blocks in an explicit SRT task.

Error Rate Increased in DLD

Interestingly, we did see an increased error rate in adults with DLD throughout both the implicit and explicit SRT tasks. We can interpret these errors in several ways, including a difference across groups in mapping a response to a stimulus, in selecting the correct motor program, in attention, or in weighting of the speed/accuracy trade-off. Any of these explanations are plausible and may have different interpretations within a neurobiological model:

1. *Stimulus–response mapping:* Mapping a stimulus to a response (stimulus–response associations or nonarbitrary visuomotor mappings) appear to initially be represented in the medial temporal lobe before transitioning to the caudate nucleus (Poldrack et al., 2001; Schendan et al., 2003). One study in people with cerebellar damage found increased errors and overall response times (the latter of which we would also expect in DLD but could not measure online) but also showed reduced sequence learning (Gómez-Beldarrain et al., 1998); a recent study has implicated cerebellar differences in children with DLD (Asaridou et al., 2023). A previous study in children with DLD showed that reaction times were slower, although the sequence-random difference was the same between groups, indicating preserved implicit learning (Gabriel et al., 2012). Those reaction times normalized when participants used a touchscreen instead of a button box, which no longer required stimulus–response mapping.
2. *Motor program selection:* Children with DLD show slower and/or more variable motor responses across a variety of tasks (Hill, 2001). It is possible that participants know the correct mapping from stimulus to motor output but select the wrong motor program more often than typical participants. Selecting the correct motor program among the options is thought to be a primary function of the basal ganglia, with motor programs inhibited by the output nuclei and correctly (or incorrectly) disinhibited by the activation of the striatum (Grillner et al., 2005). This could also explain the results above with the touchscreen (Gabriel et al., 2012), as instead of selecting from one of four small discrete movements (fingers), participants were using a larger effector (arm) and moving it continuously with real-time feedback.
3. *Attentional differences:* The increase of errors across blocks within each task could also indicate a lowering of attention as the task continues. Children with DLD demonstrate difficulties with sustained attention (Smolak et al., 2020). However, if that were the case, one might expect an increase only in latter blocks as the task continues or an accelerating rate of errors in the DLD group, which was not observed (see Table 3 and Figure 3). In future studies, a measure of sustained attention could be captured as a covariate for errors to disambiguate possible causes.
4. *Speed/accuracy trade-off:* The error rate throughout the study was low for both groups (see Figure 3), although elevated for the DLD group during each block. Errors increased throughout each task, resetting during the explicit task to an error rate somewhat above that of the first block of the implicit task. All motor responses are inherently balancing speed and accuracy. Participants can be instructed to prioritize one over the other, with resulting differences in their behavior. Here, we instructed participants to press the buttons "as quickly and accurately as possible." There exist direct measures incorporating speed and accuracy together (e.g., Urry et al., 2018; Vandierendonck, 2017), but those are not available to us due to the online nature of our study: Raw reaction times are not interpretable between participants due to variable computer equipment lag. Future study could examine this directly.

Generally, little work appears to investigate cognitive attributes or neural substrates that might mediate increased (nonlinguistic) errors in DLD or errors in SRT tasks generally, so future work is needed to resolve this question.

Sequence Recall Reduced in DLD

Participants in the DLD cohort were also significantly less able to recreate the sequence, even after explicitly memorizing and repeating it (e.g., “three-four-two-three ... ”) and performing it during the sequence tasks (see Figure 4B). This could represent a working memory difference, and indeed children with DLD show deficits in working memory and sustained attention (Lukács et al., 2016; Smolak et al., 2020). Memorizing the sequence is something of a digit span task, which appears to be reliant on the basal ganglia and cortical (temporoparietal) regions (Geva et al., 2021). However, the same percentage of participants in both groups initially recited the sequence correctly after studying it for 2 min (see Figure 4B; 76% correct in each group). The inability to recreate the sequence after learning could also be another effect of the proposed difficulty in stimulus–response mapping or motor program selection: Even if participants remembered the sequence verbally, they may have had difficulty performing it. In future experiments, we would recommend asking participants to both perform and recite the sequence after learning to try to disambiguate these possibilities. In contrast to other explicit paradigms, we intentionally reduced working memory load by placing the sequence to be learned on the screen; participants were given time to memorize it in advance but were not penalized as this could have adversely affected only the DLD group while not relating to the neural and cognitive constructs under study.

Overall, our results do indicate residual difficulties in adults with DLD in functions that are likely reliant on the basal ganglia. However, these differences may not be in strictly procedural or sequence-based learning, as these adults with DLD showed equivalent sequence learning. We also did not see any evidence of explicit and/or declarative mechanisms compensating for deficits in implicit mechanisms, contrary to Ullman and Pullman (2015). In fact, those participants in the DLD group who had more access to explicit knowledge performed worse (see Figures 5A and 5B), whereas those in the typical language group with more explicit knowledge performed better. This could explain previous results showing group differences in “implicit” tasks in which participants may actually be acquiring explicit knowledge.

Neurobiological Predictions Based on Behavioral Findings

The procedural (circuit) deficit hypothesis defines very wide swaths of subcortical mechanisms as part of procedural learning, the entire basal ganglia and all of its interconnected circuitry, though converging evidence focuses on the striatum and caudate nucleus specifically (Ullman et al., 2024). Indeed, a careful analysis of our behavioral results here may indicate a more focal deficit that could be assessed directly in the future. For example, if increased errors are indeed due to differences in the caudate nucleus or cerebellum, we may be able to relate error rate to microstructural properties of these regions in individual participants (Asaridou et al., 2023; Krishnan et al., 2022). If participants with DLD are unable to move stimulus–response mappings from initial medial temporal lobe to anterior striatum (Schendan et al., 2003), we would expect to find extended increased medial temporal lobe activity in a DLD cohort during an SRT task. Furthermore, additional cognitive mechanisms not specifically addressed in the studies in neurotypical adults are thought to be impacted in adults with DLD (e.g., attention, working memory). As we intentionally reduced the working memory load in both tasks, studies with a larger working memory load may have found other results. Similarly, although neurotypical participants seem to use minimal cortical resources to perform SRT tasks (Hardwick et al., 2013; Janacsek et al., 2020), it is possible that adults with DLD would recruit additional working memory/attentional resources to complete the task. Future study would need to evaluate this directly.

Limitations

Participants Gaining Explicit Awareness of Sequence During Implicit Task

In order to differentiate between implicit and explicit procedural learning, we tried to minimize explicit learning in the implicit SRT task. Some previous studies have done this with a dual-task model, but that would complicate the development of an identical explicit version. A previous study indicated that additional random keypresses does not hinder learning (Chambaron et al., 2006), so here we masked the sequence by interleaving random button presses after every two sequence repetitions. This did appear to be successful in reducing explicit awareness following the implicit sequence learning during pilot testing: Without interstitial random keypresses, 100% of the seven pilot participants noticed a sequence, in line with the original results from Nissen and Bullemer (1987), in which all participants who were asked reported noticing a sequence. With 15 extrainterstitial keypresses per block, 66% of six pilot participants noticed a sequence. When increased to a pseudorandom 30–45 keypresses per block (10–15 randomly added after each two complete repetitions of the sequence), 42% of pilot participants noticed a sequence. Thus, while we have increased the relative balance of implicit learning during the implicit task, some participants are still gaining explicit knowledge while performing the implicit learning task.

Online Data Collection

Due to the COVID-19 pandemic, our project utilized completely online data collection. The SRT paradigms were developed using PsychoPy online (hosted on

Pavlovia.org), which provides the best precision for response time tasks across a wide range of platforms studied: 3.5 ms (Bridges et al., 2020). All response times collected online, regardless of platform, cannot be compared in their raw states between individuals, as different computers, keyboards, and browser combinations will have different lags and thus different baseline response times (Bridges et al., 2020). It has been shown that those with DLD demonstrate overall slower response times than their peers with typical language (Zapparrata et al., 2023); it has therefore been vital to measure learning as the difference between performance in early and late blocks, rather than compare raw response times, regardless of data collection methods. Even so, some SRT studies do not look at this "sequence-random" difference. We are confident in the response time differences within participant here, given the high level of precision. We were, however, unable to compare raw response times between groups to measure the underlying motor slowing that would be expected (Zapparrata et al., 2023). Future, in-person data collection would be needed to evaluate whether, as in children, adults with DLD show slower reaction times than their peers with typical language.

Online data collection also required modification of the Fidler protocol for identifying adults with language impairment (see Operationalizing DLD section). We have ensured that our participants do not report any neurological basis for their language difficulties (e.g., anyone with multiple concussions was excluded) and do not report a hearing difference. We also did not include anyone near the boundary between (putatively) typical language and DLD. However, given that we needed to modify the Fidler protocol to change, for example, "touch the green circle" to "click the green circle," we cannot be sure that we were capturing exactly the population that others using the in-person protocol would test. Preliminary examination of in-person versus online performance on the task is ongoing but promising. Furthermore, redoing all analyses in this study with the 15 participants in each group with the most extreme scores (i.e., furthest from the cut-point) resulted in the same conclusions: no significant differences in the motor learning index, worse explicit recall in the DLD group, and increased errors in the DLD group (now a significant interaction with task rather than main effect). Therefore, we are convinced that we are capturing some actual variation in language ability between the groups. The ability to test participants online enabled us to begin data collection during extended COVID-19–based shutdowns but also eliminates the burden on research participants to get to the laboratory, enabling us to recruit more broadly across the country. Online versions of screeners and tasks will hopefully become more common and have their own norms for ease of administration and increased access.

Variations in SRT Paradigms

Different types of explicit instruction have been used throughout the literature to encourage explicit learning in SRT paradigms. In order to match the explicit SRT task as closely as possible to the implicit SRT task, we chose to inform participants about the sequence, have them memorize and repeat the sequence, and have the sequence on the screen during the task to attempt to reduce working memory load. However, results may have been very different if participants were, for example, supposed to discover and memorize the sequence by trial and error (e.g., Wilkinson et al., 2009). Similarly, we used 10-item sequences (rather than shorter, five-item sequences) as longer sequences are less likely to come to explicit awareness, but we also used deterministic sequences rather than probabilistic. We also, by nature of needing to study both implicit and explicit learning in the same participants, always had the participants perform the implicit task first, followed by a buffer of other tasks, then the explicit task. Thus, during the explicit SRT task, participants already knew how to do the task, and some may have already automatized the stimulus–response mapping.

Interpreting Neurobiological Effects From Behavior

Finally, we have attempted to position our work in the literature by incorporating research regarding the neural correlates of various tasks. It is inherently impossible to specify exactly what neural mechanisms might be in play without measuring them directly, but ideally future research can follow on these interesting behavioral results to build a more fully specified neurobiological model of DLD in adults.

Conclusions

In this study, we evaluated the ability of adults with DLD to learn sequences of button presses. We designed two versions of this SRT task to incorporate more implicit and more explicit learning. We hypothesized that adults with DLD would demonstrate reduced learning on the implicit SRT task due to the reliance on such tasks on striatal regions thought to be impaired in DLD (Krishnan et al., 2022; Ullman et al., 2024). Instead, adults with DLD showed equivalent sequence learning compared to peers with typical language. They did, however, show increased errors and were less able to recreate the sequence learned explicitly. This could indicate problems with explicit learning on the SRT task, rather than implicit learning. Future research is needed to understand neural differences driving the behavioral differences seen here in order to develop a neurobiological model of DLD in adults.

Data Availability Statement

The data set and analysis scripts are available in Supplemental Materials S1–S3.

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