Sequence learning on motor and non-motor tasks in people who stutter

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Abstract

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The purpose of this study was to investigate sequence learning in people who stutter (PWS) and people who are typically fluent (PWTF) using both implicit and explicit sequence learning paradigms while controlling for motor performance. PWS are thought to have underlying neural differences that impact motor skill learning with further influence on motor sequence learning. In this study, we employed sequence-based learning paradigms to determine the impact of motor output demands on implicit and explicit sequence learning. A total of 28 participants (PWTF = 19; PWS = 9) were recruited for this study, which does not yet meet our *a priori* sample size estimate of 21 participants per group needed to detect large effects. Participants completed a serial reaction time task (SRTT) which measured their ability to learn a 10-item sequence with manual motor output in both implicit and explicit contexts in which the presence of a sequence was either concealed or disclosed, respectively. Participants also engaged in a visual statistical learning (VSL) task to measure implicit sequence learning when motor output was not required.

Our hypothesis was largely influenced by theorized differences in striatal learning mechanisms in PWS. We hypothesized that PWS would demonstrate less motor learning on implicit tasks when compared to PWTF while no significant differences would be expected on explicit tasks. Second, we hypothesized no significant differences in performance on the non-motor implicit tasks between PWS and PWTF indicating that when motor demands are not a factor, learning is the same. Initial data analysis on a small set of participants revealed no significant group differences across all three tasks, although analyses will be repeated when full datasets are collected. Further investigation is necessary to explore the impact of manual motor output on sequence learning using explicit and implicit paradigms.

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1. INTRODUCTION

Developmental stuttering is a childhood onset speech disorder that affects approximately 5-8% of children (Reilly et al., 2009; Yairi & Ambrose, 1992). Typically, onset occurs between two and five years of age, a period that coincides with extensive speech and language development (Guitar & Peters, 2013; Yairi & Ambrose, 1992). While 75% of children who stutter spontaneously recover during childhood, the disorder can persist into adulthood, impacting around 1% of the general adult population (Craig et al., 2002; Yairi & Ambrose, 2013, 1999). The cases that do not resolve are referred to as persistent developmental stuttering (PDS), which is a neurodevelopmental disorder commonly characterized by speech fluency differences in the form of sound or syllable repetitions and audible and inaudible sound prolongations (Bloodstein et al., 2021). These result in less fluent and rhythmic speech (Wingate, 1964). Secondary behaviors such as facial grimacing, eye-blinks, and excess physical movements such as neck and arm jerks can develop in both children and adults who stutter as a compensatory mechanism to attempt to minimize the severity of stuttering (Maguire et al., 2012; Riva-Posse et al., 2008). People who stutter (PWS) may experience an overall lower quality of life including greater instances of teasing and bullying, an increased risk for mental health disorders, reduced participation in social activities, and lower vitality (the measure of an individual's energy level and fatigue) (Craig et al., 2009; Erickson & Block, 2013).

In this study, we explored motor learning abilities in PWS. Differences in motor control in PWS suggest that differences are not solely confined to the domain of speech. Rather, it is a more expansive disorder of motor control that manifests primarily in the speech domain because of the timing and sequencing demands required for fluent speech production (Etchell et al., 2014). This is consistent with the literature that PWS show differences in motor control in non-speech domains when compared to people who are typically fluent (PWTF). For example, children who stutter show deficits across motor batteries of gross and fine motor skill including difficulties with balance, finger pointing, and postural stability (Howell et al., 2008). Adults who stutter demonstrated differences in non-speech orofacial movements, finger flexion movements, and finger tapping (Max et al., 2003; Smits-Bandstra et al., 2006). The differences in motor movements and speech production in PWS point to underlying neural differences that if further studied may lead to a fuller understanding of the causes and correlates of stuttering. Furthermore, this may lead to more effective and targeted treatments for those seeking these options. To investigate the neural underpinnings of developmental stuttering in adults, we assessed an area that is thought to be affected in PWS: motor learning, specifically motor sequence learning.

1.1 NEURAL DIFFERENCES IN STUTTERING

Stuttering researchers have investigated neural differences in PDS for decades. While a variety of evidence and findings have been reported, pinpointing one network of the brain that is the main determinant of stuttering has been unclear. In large, the cortico-basal ganglia-thalamocortical motor circuit (CGBT loop) is greatly discussed and researched. One of the functions of the CBGT loop is initiating or terminating articulatory gestures within a syllabic motor program at the appropriate time by activating or monitoring neurons in an initiation map in the supplementary motor area (Chang & Guenther, 2020; Watkins & Jenkinson, 2016). An important set of structures in the loop is the basal ganglia, which are a group of subcortical nuclei including the caudate nucleus and putamen, both of which play a role in speech and language. Evidence that PDS can be attributed to abnormal function of the basal ganglia, specifically the putamen in the left hemisphere, has been primarily reviewed by Alm (2004). He proposed that deficits in basal ganglia output to the supplementary motor cortex causes disruptions in the production of timing cues that are used to initiate speech sound production. The putamen, within the basal ganglia, is a key part of the CBGT loop thought to be dysfunctional in stuttering (Alm, 2004; Chang & Guenther, 2020). This finding was seen within our lab's research in which microstructural differences were seen in the left putamen and caudate nucleus (Cler et al., 2021). In particular, motor skill learning relies on different subcortical regions moving from the caudate nucleus to sections of the putamen. Anterior portions of the putamen are thought to be more important for earlier stages of learning while posterior portions fine-tune performance in later stages of acquisition (Floyer-Lea & Matthews, 2005; Phane Lehé et al., 2005). These findings are further supported by imaging studies that found more posterior activations when motor sequences were well practiced (Bapi et al., 2006; Doyon et al., 2001; Grafton et al., 1992). Of course, activation of the putamen is not limited to sequence learning. It is also hypothesized to support spatial cognitive aspects of other motor learning tasks such as sensorimotor adaptions (Seidler et al., 2006).

Impairment of the basal ganglia can lead to an increase in compensation and activation from the cerebellum (Kotz et al., 2009). In stuttering literature, this ideology is the foundation for another behavioral model that may explain the differences in neural substrates in PWS. The cerebellum integrates sensory and motor commands, received from the primary motor cortex, to predict outcomes of anticipated movements. Differences between the generated outcomes and the intended ones are used to adjust the ongoing movements through signals returned to the cerebral cortex (Busan, 2020; Doyon et al., 2001). Over-activation of the cerebellum in individuals who stutter is hypothesized to be correlated with excess error detection between predicted sensory consequences and the actual ongoing movements performed by the individual (Chang et al., 2019; Max et al., 2004). Neuroimaging studies have reported abnormal cerebellar activity in PWS. A few of those studies include an fMRI study which identified overaction of the right cerebellum (Lu et al., 2010) and heightened cerebellar activity in stuttering speakers that declined with implementation of fluency treatment (Bauerly & de Nil, 2011).

Given theoretical and empirical findings of differences in the putamen (Alm, 2004; Chang & Guenther, 2020; Cler et al., 2021) and cerebellum (Chang et al., 2019), we hypothesize that non-speech tasks that rely on these regions may also be impacted in PWS. This has been shown in cerebellar-focused tasks (Max et al., 2004). In this project, we focused on tasks relying on the putamen, and specifically assessed non-speech sequence learning, in both motor tasks (implicit and explicit learning, which rely on a different balance of neural substrates) and a sequencing task in the visual (i.e., non-motor) domain.

1.2 MOTOR LEARNING DIFFERENCES IN STUTTERING

In essence, motor learning is a broad term that refers to the idea of producing effective movements. To be more specific, motor learning can be defined with a two-part operational definition adapted from Krakauer et al., 2019 who reported that motor learning is composed of (i) skill acquisition, the process of identifying an appropriate movement given a particular task and executing the chosen action with accuracy and precision and (ii) skill maintenance, the ability to maintain performance of an action at the attained skill level under changing circumstances of the environment.

One area of motor learning that is commonly studied is motor sequence learning. Sequence learning is a subset of motor learning that pertains to how a given set of actions become organized in a temporal order to achieve the completion of desired action or outcome. Motor sequence learning is thought to be relevant to speech because individual phonemes/syllables must be appropriately sequenced and timed with movements of the mouth and tongue to execute production of fluent speech (Krakauer et al., 2019). Currently, this type of learning has been primarily studied by having participant learn the order of a sequence and perform each movement as rapidly and well executed as possible.

1.2.1 *Serial Reaction Time Task (SRTT)*

The most prominent paradigm used to study sequence learning is the Serial Reaction Time Task (SRTT) (Nissen & Bullemer, 1987; Robertson, 2007). Typically, participants are instructed to respond to a cue using finger presses on buttons to complete a series of movements in a predetermined order. Participants are encouraged to respond to each cue as fast as possible without anticipating it. Usually unbeknownst to the participant, some blocks of stimuli follow a fixed sequence (e.g., a constant sequence of 10 elements) to allow participants to learn the order through practice and repetition. In other blocks, stimuli occur in a pseudorandom order. Often, in stuttering literature, participants are informed about the existence (and specific order) of the sequences prior to the task (i.e., explicit model) (Janacsek et al., 2020; Krakauer et al., 2019). Many studies outside of stuttering use an implicit model in which the targeted sequence is not directly provided prior to the start of the task. Instead, the participants unconsciously learn the order via practice. The stuttering SRTT literature (reviewed below) has both implicit and explicit paradigms, which can affect the interpretation of the studies.

Traditionally, total reaction time or the time from cue onset to pressing of the button is the outcome measure for SRTTs. Implicit learning is examined by comparing the differences in reaction times between sequence and random blocks (the S-R difference). Importantly, the S-R difference provides a measure of learning that is independent of variables that may affect improvement in performance such as learning the mapping between targets or fatigue. If implicit learning were to take place, a decrease in reaction time would occur across all sequence blocks suggesting that unconscious learning of the specific sequence has taken place. The same decrease in reaction time would not be seen on random blocks as there is no sequence to learn implicitly. Although the S-R difference provides a sequence specific measure, it may still be influenced by cognitive factors including changes in motivation/attention, anticipation of movements, and attempts to find a new sequence in the random blocks (Krakauer et al., 2019).

Drawbacks of the SRTT include the difficulty of distinguishing a participant's reaction time from their movement time. This makes it difficult to identify a participants' improved knowledge of the sequence order versus an improvement in execution of the finger movements to indicate one's response. Additionally, in an SRTT accuracy is defined either "correct" or "incorrect" without the concern for acuity of a movement. Despite the shortcomings, SRTT allows for implicit learning of the sequence without the influence from explicit knowledge of the entire sequence (Krakauer et al., 2019).

While SRTTs require a manual motor output to engage in learning (button presses), non-motor dependent tasks may be used to assess implicit learning as well. The visual statistical learning (VSL) task does not use motor responses for either the learning or as the index of learning (Turk-Browne et al., 2005; Turk-Browne et al., 2009). Rather, the task is divided into two sections: (1) the familiarization phase and (2) the test phase. Within the familiarization phase, participants are asked to monitor a stream of stimuli comprised of shapes that have sequential relationships. Once the full stream of stimuli is presented, participants enter the test phase in which they tasked with identifying triplets that seem most familiar to them in a two-alternative forced choice test. Implicit learning of the sequence is demonstrated through accurate identification of the triplet that is consistent with the original stimuli shown. In this study, both the SRTT and VSL task was performed since the latter task does not require motor output to engage in the learning process. (Krakauer et al., 2019; Turk-Browne et al., 2009).

1.2.2 *Neural Bases of Implicit and Explicit Learning*

The term implicit learning or procedural learning refers to unconscious learning of complex information without prior or verbalizable knowledge of the underlying structure or sequence. It is a process that is non-intentional (Krakauer et al., 2019). A common way to assess implicit learning is through motor sequences and measurement of reaction time. It is thought that implicit learning has occurred when performance of sequences becomes faster. On the other hand, explicit learning is a conscious form of learning that generates verbal knowledge of movements performed and relies on declarative processes. The caudate nucleus and the putamen are key contributors in implicit motor learning (Janacsek et al., 2020). Similarly, explicit learning utilizes the regions mentioned above but also relies heavily on the medial temporal lobe (Rieckmann et al., 2010; Schendan et al., 2003).

1.2.3 *In stuttering*

Several studies have used implicit and explicit sequence learning paradigms to explore theorized motor sequence learning differences between PWS and PWTF. As discussed, sequence learning is thought to be relevant to speech as fluent speech requires appropriate timing and sequencing of independent phonemes/syllables/words to be performed quickly and accurately in the correct order (Krakauer et al., 2019). This has been studied in the speech and non-speech domain. We focused on the non-speech domain because there is an abundance of literature on sequential motor control and whether differences in motor control appear across all motor systems.

Therefore, it may be beneficial to study limb movements. Thus, all studies reviewed utilized a non-speech sequencing task known as a finger tapping task while studies using speech sequencing tasks were excluded. However, differences in methodological details within stuttering literature limit the interpretation and translation of these findings to be able to draw conclusions and apply them to evidence-based practice (refer to Table 1 for further details). Our ability to interpret the results to determine the predicted neural differences and underlying motor learning outcomes in stuttering were impacted by the following reasons: (1) Studies utilized either an implicit or explicit motor learning paradigm instead of incorporating both and (2) Studies differed in presentation of stimuli.

In stuttering literature, five studies evaluated implicit or explicit motor sequence learning in individuals who stutter. Of these studies, only one used an implicit non-speech motor sequence learning task to investigate learning of new motor skills between children who stutter (CWS) and children who are typically fluent (CWTF) (Tendera et al., 2020). Tendera et al. (2020) reported that children who stutter demonstrated lower performance accuracy than CWTF on the first day of the finger tapping task and improved to the performance level of PWTF on the second day. The difference in performance in CWS may indicate that deficits are present in the caudate nucleus and putamen both of which are key contributors in implicit motor learning (Janacsek et al., 2020). Similarly, differences in implicit learning may also be found in adults. Therefore, our study focused on adults who stutter, as implicit non-speech motor skill learning in the adult population has undergone limited investigation.

The four remaining studies used explicit non-speech sequence learning tasks to explore motor learning in PWS (Bauerly & de Nil, 2015; Korzeczek, et al., 2020; Smits-Bandstra & de Nil, 2013; Smits-Bandstra et al., 2006). The tasks were classified as explicit because participants were notified and visually shown a pattern prior to the initiation of the experimental task. Although methods have varied, three studies found an overarching theme of PWTF demonstrating shorter and more rapid decreases in reaction times when compared to PWS (Bauerly & de Nil, 2015; Smits-Bandstra & de Nil, 2013; Smits-Bandstra et al., 2006). More specifically, Smits-Bandstra and de Nil (2013) reported that PWS demonstrated significantly longer within-chunk intervals, but no significant changes on between-chunk intervals over a practice period when compared to PWTF. This suggested that unconscious automatization and retrieval of chunks from memory/procedural systems of PWS may be less efficient than in normally fluent individuals while learning of stimulus based on prior experience with the sequence was functional (Klapp, 1995, 2003; Smits-Bandstra & de Nil, 2009). The authors indicate that these results may further highlight the potential deficiencies in the neural structures related to implicit learning while indicating that explicit mechanisms or declarative systems remain intact. However, they did not study this directly. In contrast, Korzeczek et al. (2020) reported movement speed and accuracy of PWS to be at a lower level than PWTF initially, but after a training period in which 160 repetitions of the sequence were completed, PWS caught up to the performance level of PWTF. The authors speculated that the large number of repetitions completed by participants during the initial block may have masked very early learning changes (Smits-Bandstra & Gracco, 2015). They also indicated that reduced complexity of the five-item sequence used may have been too low to detect motor learning deficits in PWS as compared to the ten-item sequences used in the other studies (Five: Korzeczek et al., 2020; ten: (Bauerly & de Nil, 2015; Smits-Bandstra et al., 2006; Smits-Bandstra & de Nil, 2013).

Table 1. Details of studies used in the literature review to outline the varying method sections in each study.

Study	**Participants**	**Task**	**Variables Measured**	**Type of learning**	**Results**
(Korzeczek et al., 2020)	16 PWS; 16 PWTF	Finger tapping task; written instructions provided with 5 - item sequence; if mistakes were made, asked to not correct them and move on	Motor sequence learning defined by movement speed (number of correct sequences) and accuracy	Explicit	Stronger motor learning in PWS (initially, PWS began at lower performance level, but caught up to PWTF); No significant differences in accuracy
(Smits-Bandstra & de Nil, 2013)	12 PWS, 12 PWTF	Finger tapping sequence task with focus on chunking; 10-number sequence; no pauses between stimuli; sequence repeated 30 times	Reaction Time, Between chunk intervals (BCI), Within-chunk intervals (WCI)	Explicit; Aspects of implicit present	PWTF had shorter RTs than PWS; PWS demonstrated longer WCI, but no significant changes of BCI over practice
(Bauerly & de Nil, 2015)	11 PWS (originally 12; 1 participant excluded from data due to hand cramps), 12 PWTF	single finger tapping; 10-number sequence; presented with visual signal followed by interstimulus interval of 1,2,3 seconds, then entire sequence was shown	Accuracy, reaction time, Sequence duration, time interval between first and final button press	Explicit	PWS did not significantly differ from PWTF on accuracy; More rapid decrease in reaction time in PWTF compared to PWS; PWS showed significantly slower sequence duration than PWTF
(Smits-Bandstra et al., 2006)	9 PWS, 9 PWTF	Finger tapping sequence task; 10-number sequence; order of testing is as follows: familiarization, 30 trials of finger tapping, transfer test, spontaneous speech and reading sample, retention test after 40 mins	Accuracy (measured by sequencing errors defined by incorrect substitution or missing/extra button presses), absolute sequence duration (ms), reaction time,	Explicit	PWTF demonstrated improved finger sequence reaction time relative to PWS; average accuracy rate comparable for both groups
(Tendera et al., 2020)	11 CWS, 17 CWTF	Multi-finger sequence task; visual stimuli of hamster; 10-element sequence; 900 ms response window	Accuracy, response synchrony (response time relative to stimulus onset)	Implicit	Lower accuracy and synchronous responses in CWS compared to CWTF on the first day, but caught up to CWTF on the second day

1.3 STUDY OVERVIEW AND HYPOTHESES

To add to the literature on motor and non-motor sequence learning in stuttering, in this study adults who stutter and those who are typically fluent completed three tasks: an implicit SRTT, an explicit SRTT, and a non-motor visual statistical learning task. We propose the following hypotheses:

(1) Adults who stutter will show less motor learning than controls on implicit tasks but will demonstrate no significant difference in motor learning during explicit tasks as demonstrated by smaller differences in mean reaction time between final random and sequence blocks, indicating a deficit in motor learning perhaps due to differences in the putamen.

(2) There will be no significant differences in performance on the non-motor implicit task (VSL) between adults who stutter and adults who do not stutter, indicating that when motor demands are not a factor, learning is the same.

2. METHODS

2.1 PARTICIPANTS

A total of 28 individuals were recruited for this study, of which 19 were people who were typically fluent and 9 had a designation of PWS. All participants were between the ages of 19-35 years old with English as either a native language (i.e., learned under the age of two) or as a secondary language. Native English speakers were screened for language disorders using the Fidler method (i.e., a 44-item modified Token Test and 15-item spelling task). A positive score indicated the presence of a language disorder, and those participants were excluded from this study. Furthermore, all participants completed a screening form in which information about their language background, history of childhood and/or current speech/language/reading/hearing concerns, and presence of other medical or neurological diagnoses were collected. All individuals recruited into the PWS group reported a history of childhood stuttering. While treatment history was recorded, it was not controlled for in this study.

Participants provided written informed consent according to the protocol approved by the University of Washington IRB.

Table 2. Participant Characteristics.

	PWTF	PWS
N	19	9
Age	Mean = 22.39 Range = 19 - 35	Mean = 29.4 Range = 24 – 34
Gender	Man: 1 Nonbinary: 2 Women: 16	Men: 5 Nonbinary: 0 Women: 4
History of childhood stuttering	N/A	100%
Self-Report Stuttering Severity (100 mm)	N/A	Range: 6 - 45 Median: 16.5

2.2 TASKS AND PROCEDURES

2.2.1 *Implicitly learned motor sequences*

Both the implicit and explicit motor sequence learning task 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 (U, I, O, and P) and press the corresponding button when one of four areas of their screen changed colors. The presented stimuli occurred in either a random order or followed a sequence and was continuously present until the correct button was pressed. To prevent participants from selecting incorrect responses to finish the task more quickly, the next stimulus was not presented until the correct corresponding button for the given stimulus was pressed. Incorrect button presses were logged in the system as an error but did not negatively impact the participant. 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 quickly and accurately as possible.

Following the Lammertink (2020) paradigm, each participant completed seven blocks of keypresses, in which the first block and the sixth block contained randomly ordered keypresses with 20 and 60 presses, respectively. The remaining blocks were sequence blocks each containing 60 trials (i.e., keypresses) that contained one of two different 10-element sequence of stimuli presentations modeled after Clark & Lum, 2017 and Lammertink et al., 2020. In a deviation from the Lammertink (2020) paradigm, the remaining blocks 2 through 5 and 7 also incorporated 10 to 15 psuedorandom keypresses after every two sequence repetitions. This was included after piloting to deter explicit knowledge of the presence of a sequence. Reaction times on these keypresses were not analyzed. The sequences were as follows: (a) 3-4-1-2-4-1-3-4-2-1 and (b) 4-2-3-1-2-4-3-1-4-3) (a. Clark & Lum, 2017; b. Lammertink et al., 2020). Hybrid sequences were used because of their irregular movement patterns to help avoid detection by participants (Hoffmann et al., 1997; Kelly et al., 2004; Pedersen et al., 2009). The measure of interest on the SRTT was the difference in mean reaction time between the final random block (i.e., block 6) and the final sequenced block (i.e., block 7). This is also known as the motor learning index.

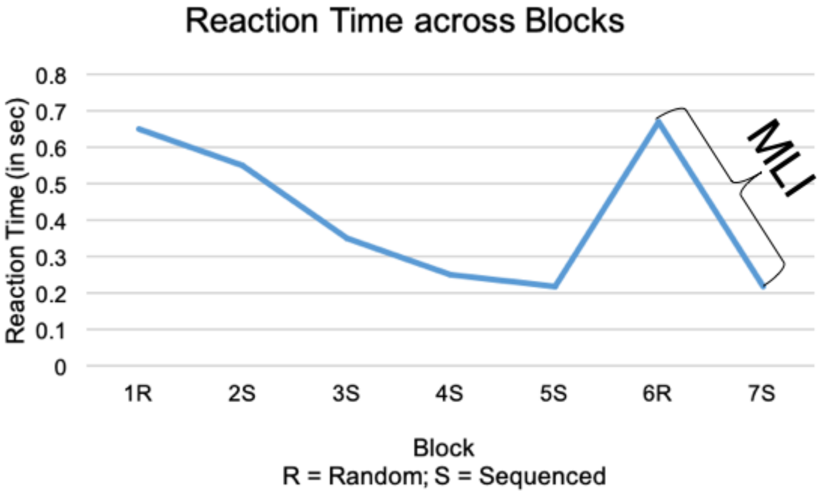

Figure 2.1. Visualization of hypothetical data displaying expected differences in reaction times across blocks of the SRTT. The motor learning index (MLI) is defined as the difference in mean time between the final random block and the final sequence block. *Figure reprinted with permission from* (Bartolo, 2022)

After completion of the implicit motor learning task, participants took part in a probe for explicit knowledge of the sequence. The probe consisted of a yes/no question in which participants were asked if they noticed anything about the keypresses. Regardless of their answer, the presence of a sequence was disclosed. Participants then completed a 30-trial free-recall task in which they were instructed to attempt to reproduce the sequence to the best of their ability (modeled after Desmottes et al., 2016; Goschke et al., 2001).

The 10-item sequence that was not used during the implicit motor sequence learning task was used for the explicit motor sequence learning task to ensure that familiarity of a prior sequence did not impact learning on a new task.

2.2.2 *Explicitly learned motor sequences*

The explicit motor learning task closely follows the implicit motor task. To promote explicit learning, prior to the start of the task, participants were shown a written representation of the sequence and instructed to memorize it to the best of their ability. The participants were asked to verbalize the memorized sequence, then as in the implicit task, the button presses were completed following the same order of random and sequence blocks. While performing the button presses in sequence blocks, the participants were provided with a written representation of the 10-item sequence for the entire duration of the block. After completion of the explicit motor learning task, participants were again asked to verbalize the target sequence and reproduce it in the same 30-trial free-recall task as used in the implicit motor learning task (Desmottes et al., 2016; Goschke et al., 2001).

2.2.3 *Non-motor implicit learning*

Non-motor implicit learning was studied through the completion of a visual statistical learning (VSL) task. The VSL task employed in the present study was modeled after Fiser and Aslin (2002) and programed on Pavlovia.org (Bridges et al., 2020). The VSL task was divided into two phases: (1) the familiarization phase and (2) the test phase. During the familiarization phase, participants were instructed to attend to a stream of stimuli presented one-by-one on the screen for a duration of 600 ms with an inter-stimulus interval of 200 ms. Unbeknownst to participants, the order of the shapes followed a sequence. The stimuli stream was comprised of 12 unique shapes that were arbitrarily grouped together into four base triplets (as shown in Figure 2.3) and were referred to as A-B-C, D-E-F, G-H-I, and J-K-L. Base triplets followed one another with equal probability so the triplets are represented repeatedly such that the transition likelihood from A→B is 100%, but from C→D, C→G, C→J are each ~33%. In the familiarization stream, a triplet may not be repeated immediately after a presentation, meaning D-E-F may not be followed immediately by D-E-F. To promote continued attention to the stimuli throughout the entirety of the task, a cover task in which participants were asked to press the space bar when they saw the same shape twice in a row was added to the original Fiser and Aslin (2002) design (Cover task modeled after 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.

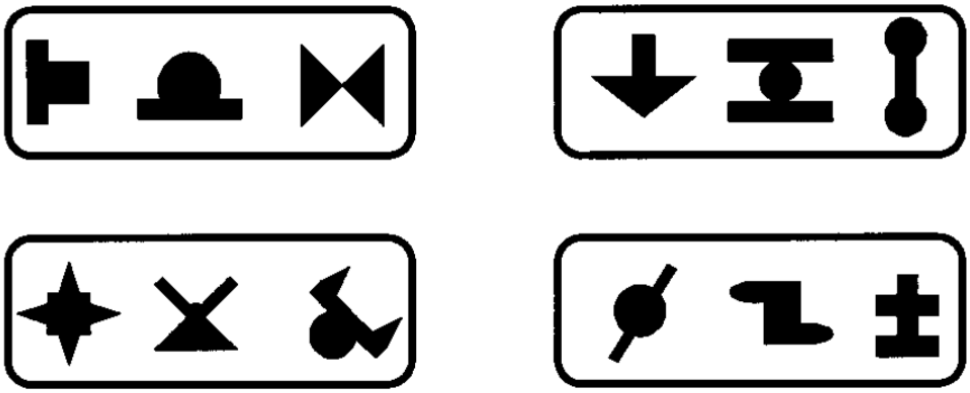

Figure 2.3. The 12 basic shapes, grouped into four triplets that are used in the VSL task. The boxes are only for demonstration purposes. Picture adapted from Fiser & Aslin, 2002.

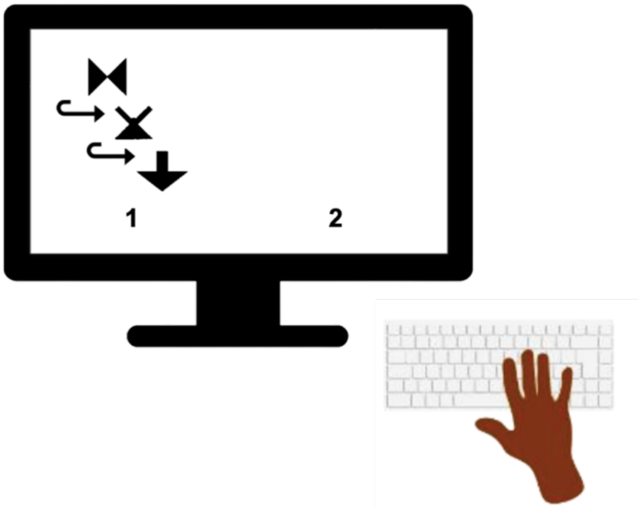

Figure 2.2. Visual representation of the two alternative forced choice task in which participants were asked to identify the true triplet from the foil triplet. On the task, the left triplet was presented first, then the right triplet, then the left again.

Following the familiarization phase, participants underwent a test phase. The test phase consisted of a two-alternative forced choice task (2AFC) that asked participants to select the most familiar sequence based on the previous familiarization phase. The participants were presented with one "true" triplet (e.g., A-B-C) and one impossible triplet (e.g., B-G-E). An impossible triplet is defined as a random combination of three of the original 12 shapes, but never occurred within the familiarization phase (Fiser & Aslin, 2002). 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 their choice (i.e., left or right stimuli). 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.

2.3 PROCEDURE

Due to the COVID-19 pandemic, all data collection took place online via Zoom. Data collection was performed by participants on their own computers, but their performance was monitored in real-time by lab personnel over Zoom. Written consent was obtained prior to the initiation of tasks. 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 study at any point they desired. Participants were compensated for their time. All procedures were approved by the University of Washington Institutional Review Board.

2.4 STATISTICAL ANALYSES

Initial data cleaning and analysis was performed in R (4.0.2). Microsoft Excel was used to complete statistical analyses. Unpaired, two-sided t-tests were used to compare reaction time differences on both implicit and explicit SRTTs (S-R) and accuracy on the VSL task between groups to identify differences in motor learning. An *a priori* power analysis using GPower determined that with 42 participants (21 = PWS; 21 = PWTF), a power of 0.8, and alpha of 0.05, we would be able to detect large effect sizes (Cohen's d = 0.8) between the groups, whereas anything smaller would not be detected.

3. RESULTS

Given the online mode of this study, three participants in the typically developing group experienced technological difficulties during the VSL task resulting in the loss of data. Therefore, the analysis to compare accuracy on the VSL task between groups were completed without the data from three typically fluent participants. All other analyses were completed with all participants included (PWTF = 19, PWS = 9). These results are preliminary, as we have not completed data collection to meet our *a priori* group size targets.

3.1 IMPLICIT SRTT

Using the motor learning index as a measure of performance (i.e., the reaction time of responses during the final random block minus the reaction time of correct responses during the final sequence block), both groups demonstrated motor learning on this task, although individual performances varied (see Figure 3.1). The PWS group demonstrated greater motor learning numerically as indicated by further decreased reaction times during the sequential block (M = 32.0

ms; SD = 30.9 ms) than the PWTF group (M = 14.5 ms; SD = 32.7 ms). A two-sided t-test revealed no significant differences between groups on this task *t*(26) = 1.34, *p* = 0.19.

3.2 EXPLICIT SRTT

Both groups demonstrated motor learning, although individual performance varied (see Figure 3.2). Numerically, the PWTF group demonstrated greater motor learning as indicated by further decreased reaction times during the sequential block (M = 247.3 ms, SD = 201.52 ms) than the PWS group (M = 158.0 ms, SD = 227.3 ms). The two-sided t-test revealed no significant differences between groups on this task *t(*26) = -1.05, *p* = 0.30.

3.3 VSL

On average, both groups performed above chance on this task as anticipated, although individual performances varied (see Figure 3.3). The PWTF group demonstrated higher accuracy (M = 57.2%, SD = 16.8%) than the PWS group (M = 51.7%, SD = 11.4%). A two-sided t-test revealed no significant effects between accuracy on the VSL forced choice task for the two groups *t(23)* = -0.87, *p* = 0.39.

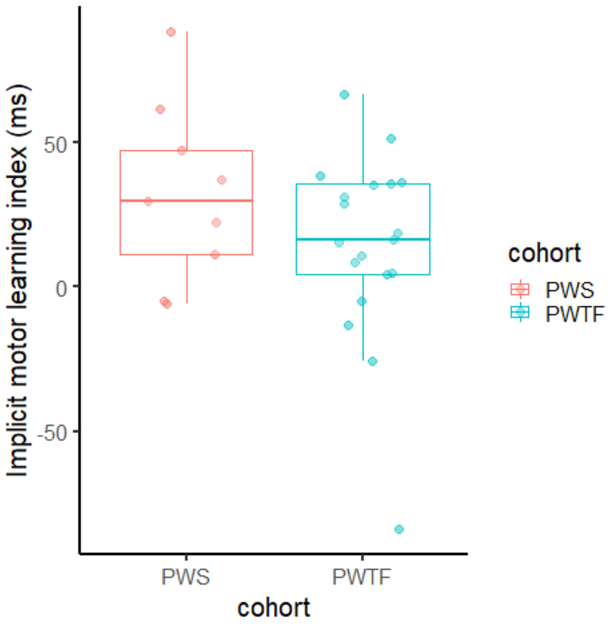

Figure 3.1 Distribution of individual differences on the motor learning index (i.e., difference in mean reaction time between the final random block and final sequence block) of the implicit SRTT. Larger numbers indicate more learning. No significant differences were found between the two groups' performances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

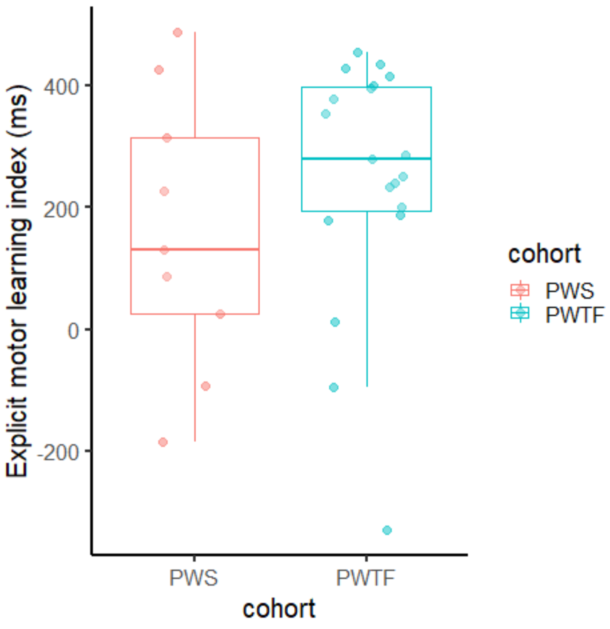

Figure 3.2. Distribution of individual differences on the motor learning index of the explicit SRTT. Larger numbers indicate more learning. No significant differences were found between the two groups' performances on the task.

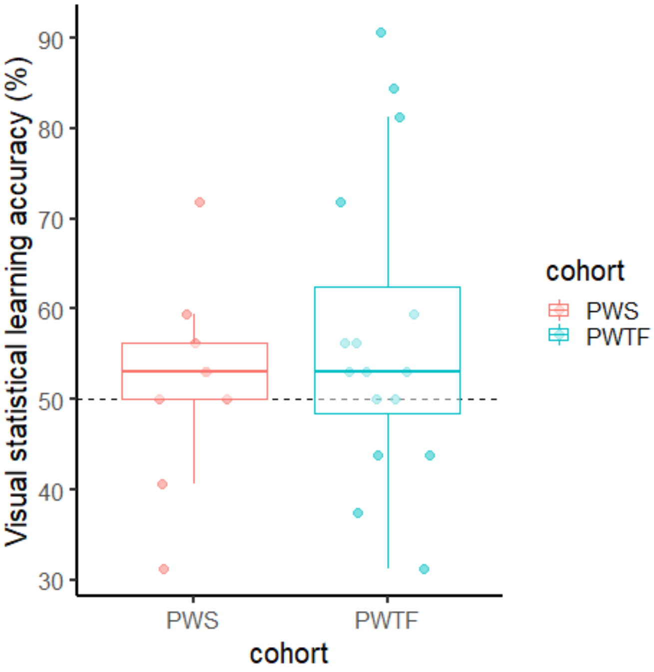

Figure 3.3. Distribution of individual accuracies on the VSL forced choice task. No significant differences were found between the two groups' performances on this task.

4. DISCUSSION

The purpose of this study was to investigate reported differences in sequence learning in PWS and PWTF using both implicit and explicit sequence learning paradigms. PWS are thought to have underlying motor differences that may impact sequence learning. Therefore, the overarching question was whether motor sequence learning was impaired in PWS when controlling for motor performance. The SRTT, a motor-dependent task, was performed to analyze if both implicit and explicit sequence learning was impacted, whereas the VSL task evaluated implicit learning in a non-motor context. Currently, our data collection is ongoing. While statistical analysis of the current dataset yielded no significant differences in task performance between groups on all tasks, we noticed minor trends that may become more prominent with a larger sample size. For our study, two-sided t-tests were chosen because although we had a directional hypothesis, some previous studies have found that PWS showed *increased* motor learning (likely due to poorer initial performance, which is not a factor with our S-R difference measure) (Korzeczek et al., 2020; Tendera et al., 2020). Here we will interpret our results assuming that all will remain with no group differences, understanding that some trends may reach significance once the *a priori* targeted recruitment (21 participants per group) is met.

4.1 DIFFERENCES IN EXPLICIT MOTOR LEARNING PARADIGMS

A key aspect of our study was to explore motor sequence learning differences in PWS and PWTF using implicit and explicit sequence learning paradigms. While several studies utilized explicit sequence learning paradigms to explore motor learning differences between these groups (as shown in Table 1), methodological details and procedures varied. Methodological differences between prior studies and our current study are outlined as follows:

(a) Smits-Bandstra & de Nil (2013), Bauerly & de Nil (2015), Smits-Bandstra et al. (2006), and Korzeczek et al. (2020) do not include random blocks during their finger tapping sequence tasks. Rather, "catch trials" were implemented to prevent response anticipation by the participants, minimizing anticipation effects on reaction time (Smits-Bandstra & de Nil, 2013; Bauerly & de Nil, 2015; Smits-Bandstra et al., 2006). In these studies, individual or raw reaction times were compared across participants. Reaction time was measured as the time (ms) from onset of the visual sequence presentation to the first button press with anything falling outside two or three standard deviations from an individual's mean were considered outliers and excluded (Bauerly & de Nil, 2015; Smits-Bandstra et al., 2006). Bauerly and de Nil (2015) explored reaction time in the context of within chunk intervals and between chunk intervals. They found PWS to have slower reaction times on early trials with PWTF improving reaction time more quickly relative to PWS (Bauerly & de Nil, 2015). In our study, random blocks were included (refer to *2.2.1 Implicitly Learned Motor Sequences* for specific details regarding random blocks), and the *difference* in reaction times between the final sequence block and final random block represent the learning index. Further, the S-R difference was calculated from the final blocks, meaning than any initial performance differences, as captured by other studies), were not included. Only overall sequence learning was included in the final measure.

(b) Korzeczek et al. (2020) did not display the sequence on the screen throughout the duration of the task. Instead, participants were introduced to the sequence with written instructions before starting the task. In our study, the 10-item sequence was shown before the initiation of the task *and* on the screen for all sequence blocks throughout the entirety of the task to increase exposure to the sequence. The presentation of the sequence on the screen is also consistent with Smits-Bandstra & de Nil (2013), Bauerly & de Nil (2015), and Smits-Bandstra et al. (2006).

(c) Smits-Bandstra & de Nil (2013) and Bauerly & de Nil (2015), did not provide participants an opportunity to become familiar with the finger tapping tasks. In our study, participants were provided with an opportunity to familiarize themselves with the task using random stimuli presentations prior to initiation of the experimental task. Our approach more closely aligned with Korzeczek et al. (2020) and Smits-Bandstra et al. (2006) in which they incorporated a training session and familiarization task, respectively, prior to the initiation of the experimental task to help participants become familiar to the instructions/task.

(d) Korzeczek et al. (2020) instructed participants to not correct errors made while tapping the sequence, but rather to continue the sequence. Whether or not errors were corrected or not is not stated in the other studies (Smits-Bandstra & de Nil, 2013; Bauerly & de Nil, 2015; and Smits-Bandstra et al. 2006). In our study, the next stimulus was not presented until the correct corresponding button for the target stimulus was presented to prevent participants from ignoring cues and randomly hitting keys as quickly as possible, given the online mode of the data collection. Furthermore, the visual feedback promoted accurate learning of the presented sequence.

In our study, statistical analysis of motor learning indices on the explicit sequence learning task revealed no significant differences between groups. Our findings differ from prior studies in stuttering research in which significant differences were found between PWS and PWTF (Smits-Bandstra & de Nil, 2013; Bauerly & de Nil, 2015; and Smits-Bandstra et al., 2006; Korzeczek et al., 2015). The first methodological variation outlined above must be further explored to explain the differences in outcome between our current study and others. In our study, out of the seven blocks of keypresses, the first and sixth blocks were random blocks with our outcome measure as the difference in reaction time in these blocks *at the end of the task* (referred to as the motor learning index or the S-R difference). The S-R difference is the measure of choice for most SRTT studies for several reasons. To complete the task, one type of learning that takes place initially is mapping the visual stimulus presentations to the corresponding finger presses on the keyboard. If a measure consists solely of a participant's performance on a later block minus performance on an earlier block, both the mapping and the sequence learning are incorporated into the motor learning index. In regard to our explicit task, the initial mapping was accomplished during the implicit learning task, therefore, for both tasks, the S-R difference ensured that the sequence learning alone (without the mapping) was accounted for separately. Similarly, motor variability may have been greater on a beginning block while less variable near the end. Additionally, comparing reaction times at the end is beneficial because other factors including motor fatigue and attention are potential factors that can impact one group more than others. For unknown reasons many of the papers in stuttering do not report the most common outcome measure (i.e., S-R difference) as an indication for motor learning. Instead, they reported other metrics such as accuracy and reaction times on difference in reaction times from the initial block (beginning) and the final block (end).

To compare our results more directly to those of other studies, reaction times were extracted by blocks (see Figure 4.1). However, the online mode of our data collection was not conducive to interpreting raw reaction times as keyboard, operating system, and browser configurations contribute to differences in latency between activating a key and recording the keypresses.

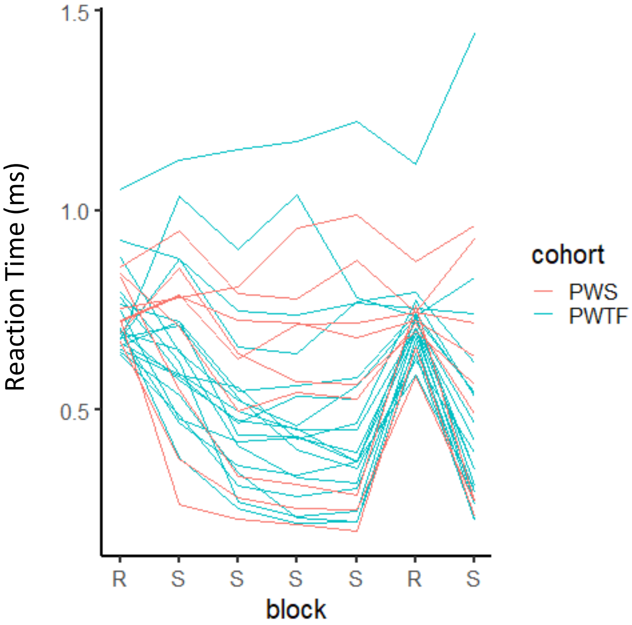

Figure 4.1. Raw reaction times of PWS and PWTF from the explicit SRTT. Data are not directly interpretable due to additional noise from online data collection: different keyboard, operating system, and browser configurations will all contribute to differences in latencies, although Pavlovia.org offers excellent precision, meaning that *differences* in reaction time are reliable and interpretable (Bridges et al., 2020).

4.2 IMPLICIT MOTOR LEARNING PARADIGM

Our statistical analysis revealed no significant group differences in motor learning between PWS and PWTF on the implicit sequence learning task. This result contradicts our hypothesis that

PWS would demonstrate less motor learning than PWTF. Our hypothesis was motivated by striatal learning mechanisms that are thought to be different in PWS and are key contributors in implicit motor learning (Janacsek et al., 2020). Based on our current results, it does not appear that there are any implicit learning differences between people who stutter and people who are typically fluent. Despite our findings, a recent study conducted by Höbler and colleagues (2022) found that implicit sequence learning was significantly reduced in people who stuttered when compared to people who were typically fluent. The authors indicate that these differences in performance may have parallels to differences in neural substrates including the basal ganglia, in particular the caudate nucleus and putamen (Höbler et al., 2022).

Although sequential learning is related to speech, the results bring to question how finger tapping is related to the sequencing of phonemes/syllables/words. Finger tapping/pressing down on the keyboard is a more discrete movement compared to speech in which multiple features (i.e., articulators, breathing pattern, planning of sounds) must be coordinated to produce speech accurately and intelligibly.

4.3 VISUAL STATISTICAL LEARNING TASK

No significant differences on accuracy were found on the VSL forced-choice task between groups, indicating that when motor demands are not a factor sequence learning is similar. This finding is consistent with our hypothesis in which we did not expect to see differences in accuracy between PWS and PWTF because of the non-motor nature of the VSL task; motor responses that we know to be slower and more variable in PWS were not required.

Both groups performed, on average, slightly above chance. Any minor difference between the groups may not be detected by this particular paradigm; Siegleman and colleagues (2017) outline the shortcomings of traditional visual statistical learning tasks which further highlight possible drawbacks of our own study. First, large proportions of the sample perform at chance level. This problem goes undetected because many statistical learning studies report mean group performances without reporting individual performance data. Often, individual performances tend to be at chance despite the group performance being above chance. For our study, this may mean that we need a larger sample size to see group learning more accurately and reliably. Another shortcoming is the structure of the 2AFC task in which we measured the ability to recognize "true" triplets from foil triplets. Our structure of the task resulted in testing multiple items that measured the same knowledge with the same difficulty. Rather, (Siegelman et al., 2017) suggest that more variation within the 2AFC task is necessary for better coverage of measured abilities to better capture true statistical learning.

4.4 CLINICAL IMPACT

Our current results do not outline significant differences in either implicit or explicit sequence learning between PWS and PWTF. We hope that continued data collection in our laboratory may provide important information for treatments in the future. Further research is needed to determine whether implicit treatment models (e.g., motor practice, parent feedback) or explicit treatment models (e.g., conscious strategy use, self-monitoring, drills) are more beneficial. Although future outcomes on sequence motor learning patterns are important to consider when working with PWS, as with all speech treatments it is crucial to consider a patient holistically and individually as portrayed through the World Health Organization's (WHO) International Classification of Functioning, Disability, and Health (ICF) (World Health Organization., 2001) with a stuttering specific model update from (Yaruss & Quesal, 2004).

4.5 LIMITATIONS

A key limitation of our study was our small sample size. A larger sample size is critical for identifying trends and differences in sequence learning. Our *a priori* power analyses suggested that 21 participants per group would be needed to identify large effects. Currently, both of our groups fall short of the ideal participant number in both PWTF and PWS groups by two and twelve, respectively. Our data collection is ongoing and this project will be completed in the coming months.

The COVID-19 pandemic largely influenced a rise in online data collection, which is not without challenges. All online platforms are unable to capture interpretable raw reaction times due to inherent differences in participant keyboards, operating system, and browser configurations, which all contribute to differences in latency between activating a key and recording of the keypress. However, reaction time *differences* were reliable and interpretable. Another challenge was the adaptation of the implicit SRTT and the VSL task. There is minimal research on the translation of these tasks into a virtual format. Therefore, a large component of this project was focused on piloting and adapting paradigms based on our initial outcomes. Online testing will likely continue to be a large component of research. Future research is needed to explore the validity of these paradigms to best explore sequence learning. Despite the challenges of an online format, we recognized that the one of the greatest benefits was the ability to recruit larger and more representative samples that are typically not included in research.

5. CONCLUSION

Our main findings do not lend strong support for differences in motor sequence learning between PWS and PWTF on motor and non-motor implicit and explicit learning paradigms.

Although results are as yet inconclusive, it is possible that significant differences may be found on motor sequence learning given the minor trends identified within our study once data collection reaches *a priori* targeted recruitment. This potential finding would provide further insight into neural differences of stuttering including the involvement of the putamen in motor skill learning. For our laboratory, an avenue for future research may be a neuroimaging study to further explore the neural substrates that are thought to be involved in implicit and explicit sequence learning in people who stutter. In conclusion, the current study does not provide unequivocal support for differences in motor sequence learning in PWS. Further investigation is warranted to fully assess potential differences in motor sequence learning in PWS.

REFERENCES

Alm, P. A. (2004). Stuttering and the basal ganglia circuits: A critical review of possible relations. *Journal of Communication Disorders*, *37*(4), 325–369. https://doi.org/10.1016/j.jcomdis.2004.03.001

Bapi, R. S., Miyapuram, K. P., Graydon, F. X., & Doya, K. (n.d.). *fMRI Investigation of Cortical and Subcortical Networks in the Learning of Abstract and Effector-Specific Representations of Motor Sequences*.

Bartolo, S. M. (2022). *Procedural Learning in Adults with and without Developmental Language Disorder: The Influence of Manual Motor Demands*. University of Washington.

Bauerly, K. R., & de Nil, L. F. (2011). Speech sequence skill learning in adults who stutter. *Journal of Fluency Disorders*, *36*(4), 349–360. https://doi.org/10.1016/j.jfludis.2011.05.002

Bauerly, K. R., & de Nil, L. F. (2015). *Nonspeech Sequence Skill Learning Under Single and Dual Task Conditions in Adults who Stutter. Canadian Journal of Speech-Language Pathology and Audiology* | (Vol. 39).

Bloodstein, O., Ratner, N. B., & Brundage, S. B. (2021). *A Handbook on Stuttering* (7th ed.). Plural Publishing .

Bridges, D., Pitiot, A., MacAskill, M. R., & Peirce, J. W. (2020). The timing mega-study: Comparing a range of experiment generators, both lab-based and online. *PeerJ*, *8*, e9414. https://doi.org/10.7717/peerj.9414

Busan, P. (2020, June 1). Developmental stuttering and the role of the supplementary motor cortex. *Journal of Fluency Disorders*. Elsevier Inc. https://doi.org/10.1016/j.jfludis.2020.105763

Chang, S. E., Garnett, E. O., Etchell, A., & Chow, H. M. (2019, December 1). Functional and Neuroanatomical Bases of Developmental Stuttering: Current Insights. *Neuroscientist*. SAGE Publications Inc. https://doi.org/10.1177/1073858418803594

Chang, S. E., & Guenther, F. H. (2020, January 28). Involvement of the Cortico-Basal Ganglia-Thalamocortical Loop in Developmental Stuttering. *Frontiers in Psychology*. Frontiers Media S.A. https://doi.org/10.3389/fpsyg.2019.03088

Clark, G. M., & Lum, J. A. G. (2017). Procedural learning in Parkinson's disease, specific language impairment, dyslexia, schizophrenia, developmental coordination disorder, and autism spectrum disorders: A second-order meta-analysis. *Brain and Cognition*, *117*, 41–48. https://doi.org/10.1016/j.bandc.2017.07.004

Cler, G. J., Krishnan, S., Papp, D., Wiltshire, C. E. E., Chesters, J., & Watkins, K. E. (2021). *Elevated iron concentration in putamen and cortical speech motor network in developmental stuttering*.

Craig, A., Blumgart, E., & Tran, Y. (2009). The impact of stuttering on the quality of life in adults who stutter. *Journal of Fluency Disorders*, *34*(2), 61–71. https://doi.org/10.1016/j.jfludis.2009.05.002

Craig, A., Hancock, K., Tran, Y., Craig, M., & Peters, K. (2002). Epidemiology of Stuttering in the Community Across the Entire Life Span. *Journal of Speech, Language, and Hearing Research*, *45*(6), 1097–1105. https://doi.org/10.1044/1092-4388(2002/088)

Desmottes, L., Meulemans, T., & Maillart, C. (2016). Implicit spoken words and motor sequences learning are impaired in children with specific language impairment. *Journal of the International Neuropsychological Society*, *22*(5), 520–529. https://doi.org/10.1017/S135561771600028X

Doyon, J., Song, A. W., Karni, A., Lalonde, F., Adams, M. M., & Ungerleider, L. G. (2001). *Experience-dependent changes in cerebellar contributions to motor sequence learning*. Retrieved from www.pnas.orgcgidoi10.1073pnas.022615199

Erickson, S., & Block, S. (2013). The social and communication impact of stuttering on adolescents and their families. *Journal of Fluency Disorders*, *38*(4), 311–324. https://doi.org/10.1016/j.jfludis.2013.09.003

Etchell, A. C., Johnson, B. W., & Sowman, P. F. (2014). Behavioral and multimodal neuroimaging evidence for a deficit in brain timing networks in stuttering: A hypothesis and theory. *Frontiers in Human Neuroscience*, *8*(JUNE). https://doi.org/10.3389/fnhum.2014.00467

Fiser, J., & Aslin, R. N. (2002). Statistical Learning of Higher-Order Temporal Structure from Visual Shape Sequences. *Journal of Experimental Psychology: Learning Memory and Cognition*, *28*(3), 458–467. https://doi.org/10.1037/0278-7393.28.3.458

Floyer-Lea, A., & Matthews, P. M. (2005). Distinguishable brain activation networks for short- and long-term motor skill learning. *Journal of Neurophysiology*, *94*(1), 512–518. https://doi.org/10.1152/jn.00717.2004

Goschke, T., Friederici, A. D., Kotz, S. A., & van Kampen, A. (2001). *Procedural Learning in Broca's Aphasia: Dissociation between the Implicit Acquisition of Spatio-Motor and Phoneme Sequences*. *From: Journal of Cognitive Neuroscience* (Vol. 13).

Grafton, S. T., Mazziotta, J. C., Presty, S., Friston, K. J., Frackowiak, R. S. J., & Phelpsis3, M. E. (1992). *Functional Anatomy of Human Procedural Learning Determined with Regional Cerebral Blood Flow and PET*. *The Journal of Neuroscience*.

Guitar, B., & Peters, T. J. (2013). *Stuttering: an integrated approach to its nature and treatment.* (4th ed.). Baltimore: Williams and Wilkins.

Höbler, F., Bitan, T., Tremblay, L., & de Nil, L. (2022). Differences in implicit motor learning between adults who do and do not stutter. *Neuropsychologia*, *174*, 108342. https://doi.org/10.1016/j.neuropsychologia.2022.108342

Hoffmann, J., Koch, I., & Hoffmann, J. (1997). *Stimulus-response compatibility and sequential learning in the serial reaction time task*. *Psychol Res* (Vol. 60).

Howell, P., Davis, S., & Williams, R. (2008). Late childhood stuttering. *Journal of Speech, Language, and Hearing Research*, *51*(3), 669–687. https://doi.org/10.1044/1092-4388(2008/048)

Janacsek, K., Shattuck, K. F., Tagarelli, K. M., Lum, J. A. G., Turkeltaub, P. E., & Ullman, M. T. (2020). Sequence learning in the human brain: A functional neuroanatomical meta-analysis of serial reaction time studies. *NeuroImage*, *207*. https://doi.org/10.1016/j.neuroimage.2019.116387

Kelly, S. W., Jahanshahi, M., & Dirnberger, G. (2004). Learning of ambiguous versus hybrid sequences by patients with Parkinson's disease. *Neuropsychologia*, *42*(10), 1350–1357. https://doi.org/10.1016/j.neuropsychologia.2004.02.013

Klapp, S. T. (1995). *Motor Response Programming During Simple and Choice Reaction Time: The Role of Practice*. *Journal of Experimental Psychology: Human Perception and Performance* (Vol. 21).

Klapp, S. T. (2003). Reaction time analysis of two types of motor preparation for speech articulation: Action as a sequence of chunks. *Journal of Motor Behavior*, *35*(2), 135–150. https://doi.org/10.1080/00222890309602129

Korzeczek, A., Cholin, J., Jorschick, A., Hewitt, M., & Sommer, M. (2020). Finger Sequence Learning in Adults Who Stutter. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.01543

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, *45*(8), 982–990. https://doi.org/10.1016/j.cortex.2009.02.010

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2019). Motor learning. *Comprehensive Physiology*, *9*(2), 613–663. https://doi.org/10.1002/cphy.c170043

Lammertink, I., Boersma, P., Wijnen, F., & Rispens, J. (2020). Statistical Learning in the Visuomotor Domain and Its Relation to Grammatical Proficiency in Children with and without Developmental Language Disorder: A Conceptual Replication and Meta-Analysis. *Language Learning and Development*, *16*(4), 426–450. https://doi.org/10.1080/15475441.2020.1820340

Lu, C., Chen, C., Ning, N., Ding, G., Guo, T., Peng, D., … Lin, C. (2010). The neural substrates for atypical planning and execution of word production in stuttering. *Experimental Neurology*, *221*(1), 146–156. https://doi.org/10.1016/j.expneurol.2009.10.016

Maguire, G. A., Yeh, C. Y., & Ito, B. S. (2012, April). Overview of the diagnosis and treatment of stuttering. *Journal of Experimental and Clinical Medicine*. https://doi.org/10.1016/j.jecm.2012.02.001

Max, L., Caruso, A. J., & Gracco, V. L. (2003). Kinematic Analyses of Speech, Orofacial Nonspeech, and Finger Movements in Stuttering and Nonstuttering Adults. *Journal of Speech, Language, and Hearing Research*, *46*(1), 215–232. https://doi.org/10.1044/1092-4388(2003/017)

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., & Wallace, M. E. (2004). *Unstable or Insufficiently Activated Internal Models and Feedback-Biased Motor Control as Sources of Dysfluency: A Theoretical Model of Stuttering. CONTEMPORARY ISSUES IN COMMUNICATION SCIENCE AND DISORDERS* • (Vol. 31). Retrieved from https://pubs.asha.org

Nissen, M. J., & Bullemer, P. (1987). *Attentional Requirements of Learning: Evidence from Performance Measures. COGNITIVE PSYCHOLOGY* (Vol. 19).

Pedersen, A., Küppers, K., Behnken, A., Kroker, K., Schöning, S., Baune, B. T., … Suslow, T. (2009). Implicit and explicit procedural learning in patients recently remitted from severe major depression. *Psychiatry Research*, *169*(1), 1–6. https://doi.org/10.1016/j.psychres.2008.06.001

Phane Lehé, S., Benali, H., van de Moortele, P.-F., Lé Grini-Issac, P., Waechter, T., Ugurbil, K., & Doyon, J. (2005). *Distinct basal ganglia territories are engaged in early and advanced motor sequence learning*. Retrieved from www.pnas.orgcgidoi10.1073pnas.0502762102

Reilly, S., Onslow, M., Packman, A., Wake, M., Bavin, E. L., Prior, M., … Ukoumunne, O. C. (2009). Predicting stuttering onset by the age of 3 years: A prospective, community cohort study. *Pediatrics*, *123*(1), 270–277. https://doi.org/10.1542/peds.2007-3219

Rieckmann, A., Fischer, H., & Bäckman, L. (2010). Activation in striatum and medial temporal lobe during sequence learning in younger and older adults: Relations to performance. *NeuroImage*, *50*(3), 1303–1312. https://doi.org/10.1016/j.neuroimage.2010.01.015

Riva-Posse, P., Busto-Marolt, L., Schteinschnaider, Á., Martinez-Echenique, L., Cammarota, Á., & Merello, M. (2008). Phenomenology of abnormal movements in stuttering. *Parkinsonism and Related Disorders*, *14*(5), 415–419. https://doi.org/10.1016/j.parkreldis.2007.11.006

Robertson, E. M. (2007, September 19). The serial reaction time task: Implicit motor skill learning? *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.2747-07.2007

Schendan, H. E., Searl, M. M., Melrose, R. J., & Stern, C. E. (2003). *An fMRI Study of the Role of the Medial Temporal Lobe in Implicit and Explicit Sequence Learning to sequences with attributes that do not exceed the storage capabilities of working memory (e.g., shorter, brief interstimulus delay, few intervening stimuli). For. Neuron* (Vol. 37).

Seidler, R. D., Noll, D. C., & Chintalapati, P. (2006). Bilateral basal ganglia activation associated with sensorimotor adaptation. *Experimental Brain Research*, *175*(3), 544–555. https://doi.org/10.1007/s00221-006-0571-y

Siegelman, N., Bogaerts, L., & Frost, R. (2017). Measuring individual differences in statistical learning: Current pitfalls and possible solutions. *Behavior Research Methods*, *49*(2), 418–432. https://doi.org/10.3758/s13428-016-0719-z

Smits-Bandstra, S., & de Nil, L. (2009). Speech skill learning of persons who stutter and fluent speakers under single and dual task conditions. *Clinical Linguistics and Phonetics*, *23*(1), 38–57. https://doi.org/10.1080/02699200802394914

Smits-Bandstra, S., & de Nil, L. F. (2013). Early-stage chunking of finger tapping sequences by persons who stutter and fluent speakers. *Clinical Linguistics and Phonetics*, *27*(1), 72–84. https://doi.org/10.3109/02699206.2012.746397

Smits-Bandstra, S., de Nil, L. F., & Saint-Cyr, J. A. (2006). Speech and nonspeech sequence skill learning in adults who stutter. *Journal of Fluency Disorders*, *31*(2), 116–136. https://doi.org/10.1016/j.jfludis.2006.04.003

Smits-Bandstra, S., & Gracco, V. (2015). Retention of Implicit Sequence Learning in Persons Who Stutter and Persons With Parkinson’s Disease. *Journal of Motor Behavior*, *47*(2), 124–141. https://doi.org/10.1080/00222895.2014.961890

Tendera, A., Wells, R., Belyk, M., Varyvoda, D., Boliek, C. A., & Beal, D. S. (2020). Motor sequence learning in children with recovered and persistent developmental stuttering: preliminary findings. *Journal of Fluency Disorders*, *66*. https://doi.org/10.1016/j.jfludis.2020.105800

Turk-Browne, N. B., Jungé, J. A., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General*, *134*(4), 552–564. https://doi.org/10.1037/0096-3445.134.4.552

Turk-Browne, N. B., Scholl, B. J., Chun, M. M., & Johnson, M. K. (2009). Neural Evidence of Statistical Learning: Efficient Detection of Visual Regularities Without Awareness. *Journal of Cognitive Neuroscience*, *21*(10), 1934–1945. https://doi.org/10.1162/jocn.2009.21131

Watkins, K. E., & Jenkinson, N. (2016). The Anatomy of the Basal Ganglia. *Neurobiology of Language*, 85–94. https://doi.org/10.1016/B978-0-12-407794-2.00008-0

Wingate, M. E. (1964). A Standard Definition of Stuttering. *Journal of Speech and Hearing Disorders*, *29*(4), 484–489. https://doi.org/10.1044/jshd.2904.484

World Health Organization. (2001). *International classification of functioning, disability and health : ICF.*

Yairi, E., & Ambrose, N. (1992). A Longitudinal Study of Stuttering in Children. *Journal of Speech, Language, and Hearing Research*, *35*(4), 755–760. https://doi.org/10.1044/jshr.3504.755

Yairi, E., & Ambrose, N. (2013). Epidemiology of stuttering: 21st century advances. *Journal of Fluency Disorders*, *38*(2), 66–87. https://doi.org/10.1016/j.jfludis.2012.11.002

Yairi, E., & Ambrose, N. G. (1999). Early childhood stuttering I: Persistency and recovery rates. *Journal of Speech, Language, and Hearing Research*, *42*(5), 1097–1112. https://doi.org/10.1044/jslhr.4205.1097

Yaruss, J. S., & Quesal, R. W. (2004). Stuttering and the International Classification of Functioning, Disability, and Health (ICF): An update. *Journal of Communication Disorders*, *37*(1), 35–52. https://doi.org/10.1016/S0021-9924(03)00052-2