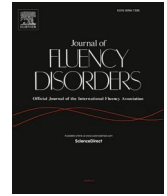




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Explicit benefits: Motor sequence acquisition and short-term retention in adults who do and do not stutter

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ABSTRACT

Motor sequencing skills have been found to distinguish individuals who experience developmental stuttering from those who do not stutter, with these differences extending to non-verbal sequencing behaviour. Previous research has focused on measures of reaction time and practice under externally cued conditions to decipher the motor learning abilities of persons who stutter. Without the confounds of extraneous demands and sensorimotor processing, we investigated motor sequence learning under conditions of explicit awareness and focused practice among adults with persistent developmental stuttering. Across two consecutive practice sessions, 18 adults who stutter (AWS) and 18 adults who do not stutter (ANS) performed the finger-to-thumb opposition sequencing (FOS) task. Both groups demonstrated significant within-session performance improvements, as evidenced by fast on-line learning of finger sequences on day one. Additionally, neither participant group showed deterioration of their learning gains the following day, indicating a relative stabilization of finger sequencing performance during the off-line period. These findings suggest that under explicit and focused conditions, early motor learning gains and their short-term retention do not differ between AWS and ANS. Additional factors influencing motor sequencing performance, such as task complexity and saturation of learning, are also considered. Further research into explicit motor learning and its generalization following extended practice and follow-up in persons who stutter is warranted. The potential benefits of motor practice generalizability among individuals who stutter and its relevance to supporting treatment outcomes are suggested as future areas of investigation.

1. Introduction

Across our activities of daily life, we rely on our ability to execute a range of movement behaviours with efficiency, precision, and skill. Whether speaking, writing or typing, our motor learning abilities allow us to acquire distinct and discrete motor acts that are

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organized in an appropriate temporal sequence, with the aim of achieving a specific task goal, such as communication (Krakauer et al., 2019; Ungerleider & Doyon, 2002). Motor learning also underlies our ability to control and adapt these movements, and to improve the speed and accuracy of their execution over practice (Krakauer et al., 2019; Luft & Buitrago, 2005). Developmental stuttering, which manifests on the initiation of verbal sequences, implicates speech motor planning and execution among persons who stutter (Max et al., 2004; Smith & Weber, 2017).

In studies of motor control and adaptation, significant differences have been found between adults who stutter (AWS) and who do not stutter (ANS) in their abilities to adjust to auditory (Cai et al., 2012; Daliri et al., 2018; Kim et al., 2020), somatosensory (Loucks & De Nil, 2012), and temporal perturbations (Cai et al., 2014) on speech tasks. These inefficiencies in sensorimotor adaptation among AWS may limit their ability to update already established speech motor plans in order to initiate, terminate, or correct speech motor production with relevant sensory feedback (Chang & Guenther, 2020; Civier et al., 2010; Krakauer et al., 2019). Studies of motor sequence learning, however, have identified differences between persons who do and do not stutter that extend beyond speech motor behaviours. As measured by changes in the speed, accuracy and stability of executing sequential movements (Magill & Anderson, 2017; Schmidt et al., 2019), persons who stutter have been found to differ in their abilities to acquire verbal sequencing skills, involving syllable production, as well as non-verbal sequencing skills, involving finger movements. Finger sequence learning has been associated with neural activity in the supplementary motor area (SMA), pre-SMA, the inferior frontal gyrus (IFG) and in striatal structures (Hikosaka et al., 1996; Luft & Buitrago, 2005; Ungerleider et al., 2002) – regions that are also relied upon for speech motor learning (Dick et al., 2019; Masapollo et al., 2021; Segawa et al., 2015). These same regions have evidenced both structural and functional differences among persons with developmental stuttering at various stages of the lifespan (Beal et al., 2015; Beal et al., 2013; Cai et al., 2014; Chang & Zhu, 2013; Chang et al., 2008; Chow et al., 2020; Desai et al., 2017; Kell et al., 2009; Sitek et al., 2016; Toyomura et al., 2011).

In studies of syllable- and finger-sequencing skills, reduced practice effects among AWS have been found on measures of sequence duration (Bauerly & De Nil, 2011, 2015), reaction time (Bauerly & De Nil, 2015; Smits-Bandstra & De Nil, 2007, 2009; Smits-Bandstra, 2010; Smits-Bandstra et al., 2006), under conditions of implicit learning (Höbler et al., 2022; Smits-Bandstra & Gracco, 2013) and divided attention (Smits-Bandstra & De Nil, 2009; Smits-Bandstra et al., 2006), and most notably among male participants (Bauerly & De Nil, 2011, 2015; Namasivayam & van Lieshout, 2008; Smits-Bandstra & De Nil, 2007, 2009; Smits-Bandstra et al., 2006; Smits-Bandstra, De Nil et al., 2013). Delays in motor sequencing performance found among AWS, when compared to ANS, have frequently been identified at baseline and on early practice trials (Korzeczek et al., 2020; Masapollo et al., 2021; Smits-Bandstra & De Nil, 2007; Smits-Bandstra et al., 2006).

Across the majority of studies, motor sequence performance among persons who stutter has been investigated by use of reaction-time (RT) paradigms (Bauerly & De Nil, 2015; Smits-Bandstra & De Nil, 2007, 2009; Smits-Bandstra & Gracco, 2013, 2015; Smits-Bandstra et al., 2006) and cued practice trials (Korzeczek et al., 2020; Masapollo et al., 2021). A review of RT investigations found that initial differences between AWS and ANS on simple, single-response RT tasks tend to decline with practice, while more complex, multi-component RT tasks tend to elicit increasing divergence in the performances of AWS and ANS with practice (Smits-Bandstra, 2010). Furthermore, RT tasks that require an immediate response tend to detect greater delays among AWS, when compared to ANS, than tasks that provide a warning cue and require a delayed response (Smits-Bandstra, 2010).

In the motor learning literature, complex motor sequences are most commonly presented in the form of a stimulus-driven RT tasks, owing to their high working memory (WM) demands in early practice (Abrahamse et al., 2010; Bo & Seidler, 2009; Howard & Howard, 1997; Nissen & Bullemer, 1987; Shea et al., 2006). The serial reaction time task (SRTT) is the most widely used experimental paradigm to measure motor sequence learning (Krakauer et al., 2019; Nissen & Bullemer, 1987). The SRTT calls on the performer to press a button that is spatially congruent with the visual stimulus presented on a screen, thereby also relying on the speed and accuracy of the performer's perceptual processing and visuomotor integration abilities. Visuomotor and visuo-perceptual inefficiencies have previously been identified among AWS (Jones et al., 2002), and may play a role in the delayed performance gains found in AWS when compared to those of ANS in SRTT investigations (Höbler et al., 2022; Smits-Bandstra & Gracco, 2013; Smits-Bandstra et al., 2006).

The finger-to-thumb opposition sequencing (FOS) task, on the other hand, involves a set of finger to thumb opposition movements that is instructed visually, but does not rely on continuous cueing by an external stimulus or on augmented feedback of performance (Korman et al., 2007; Korman et al., 2003). As such, one advantage of the FOS task is the self-paced initiation of the movement sequence, which avoids the temporal constraints pertaining to movement preparation in studies employing RT and SRTT methods. From a perspective of ecological validity, an important question that remains is whether the previously reported differences between AWS and ANS in finger movement sequencing extend to tasks on which the temporal demands of when to initiate the voluntary movements are more limited (even if there is a demand to complete the movements as rapidly as possible). The FOS paradigm has been applied across various participant groups as an explicit motor learning paradigm that demonstrates the time-course of motor skill acquisition, including on-line sequence-specific performance as well as latent off-line performance gains (Dorfberger et al., 2009; Gabbitov et al., 2014; Karni et al., 1995, 1998; Karni et al., 1994; Korman et al., 2007, 2018; Korman et al., 2017; Rozanov et al., 2010).

By use of robust motor learning paradigms, this incremental process can be observed in significant performance improvements that progress from fast “on-line” learning on early trials to slower learning over the course of hours, days, or weeks of practice (Karni et al., 1998; Luft & Buitrago, 2005; Ungerleider et al., 2002). Between practice sessions, an intermediate phase of motor skill consolidation, or “off-line” learning, can see latent gains in speed and accuracy being made, even without any additional training or exposure (Cohen et al., 2005; Karni et al., 1998; Luft & Buitrago, 2005). During practice, experience-induced neural activity initiates the process of memory consolidation (McGaugh, 2000). However, following practice, the expression of delayed learning gains has been found to depend on approximately six hours without interference of another motor sequencing task for stabilization of the memory trace, as well as on a period of sleep for additional post-training improvements to emerge (Korman et al., 2007; Walker et al., 2003). This

process of off-line consolidation is thought to be critical to the retention as well as to the enhancement of skills acquired during practice (Walker & Stickgold, 2004, 2006). Recent evidence suggests that given the opportunity for extended motor practice, beyond a single session, AWS can benefit from practising novel verbal sequences to the same extent as ANS (Masapollo et al., 2021; Smits-Bandstra & Gracco, 2015), and can also compensate for reduced baseline performance on finger sequencing tasks (Korzeczek et al., 2020).

During early practice of the FOS task, motor sequencing habituation effects in the primary motor cortex (M1) have been identified during the 30- to 40-second intervals of rest between performance blocks of the FOS (Karni et al., 1998), which positively correlate with off-line performance gains expressed the following day (Gabitov et al., 2014). With continued practice, early functional connectivity between M1 and the striatum has also been found to decrease, thereby, implicating the critical role of the M1, IFG and putamen in “motor working memory” (Gabitov et al., 2015) and motor sequence learning in early practice (Doyon et al., 2003). Although sequencing tasks involving six or more finger positions will increasingly be performed as smaller chunks of sequence segments following extended practice (Bo & Seidler, 2009; Bo, Borza et al., 2009; Verwey, 2001, 2003), the FOS that has been found to form a sequence-specific, five-element chunk in itself and may relate to typical WM capacities (Rozanov et al., 2010; Verwey, 2003). In addition to WM, studies of the FOS task have pointed toward the need for sustained attention to make performance gains in speed and accuracy (Korman et al., 2003), with adults experiencing symptoms of inattention showing reduced accuracy during on-line sequence learning as well as slower off-line memory consolidation (Adi-Japha et al., 2011; Korman et al., 2017). This may suggest an important area for consideration with regards to persons experiencing development stuttering. A higher incidence of Attention Deficit Hyperactivity Disorder symptomology and difficulties in attentional processing have previously been reported among AWS (Donaher & Richels, 2012; Druker et al., 2019; Eggers et al., 2012; Tichenor et al., 2021), with differences in attentional control also linked to WM capacities in AWS (Tichenor et al., 2022).

The role of sustained attention and explicit motor learning has not yet been explored in persons who stutter, and little is known about their ability to benefit from motor practice under self-paced and focused conditions, without external cueing or without the perturbation, augmentation or withdrawal of sensory feedback. The relevance of motor learning under explicit conditions of practice can be extended to the clinical context, in which fluency-facilitating strategies are often explicitly instructed to and practiced by persons who stutter, such as techniques involving the practice of gentle onset and prolonged speech patterns. Thus, the abilities of persons who stutter to benefit from motor practice under explicit, focused and self-guided conditions may have implications for the successful application of fluency strategies, consolidation of treatment gains, and their maintenance in the long-term.

For these reasons, the current study sought to investigate explicit motor learning and off-line consolidation in adults with persistent developmental stuttering across two practice sessions by use of the FOS task. It was hypothesized that AWS and ANS would differ at the beginning of the first practice session, with AWS completing fewer correct sequences within early practice blocks. It was also hypothesized that although these differences may diminish by the end of the first practice session on day one, further differences in consolidation may be seen with reduced learning improvements of sequencing speed and accuracy when compared with the between-session performance of ANS on day two.

Table 1
Participant characteristics by group mean, median, standard deviation, and differences.

	AWS	ANS	Difference
N	18	18	
Female	4	5	
Male	14	13	
Age	<i>M</i> = 32.56, <i>Mdn</i> = 34, <i>SD</i> = 7.28	<i>M</i> = 31.78, <i>Mdn</i> = 32, <i>SD</i> = 6.02	<i>t</i> (34) = 0.35, <i>p</i> = .73
STM LDSF	<i>M</i> = 7.39, <i>Mdn</i> = 8, <i>SD</i> = 1.46	<i>M</i> = 7.83, <i>Mdn</i> = 8, <i>SD</i> = 1.10	<i>U</i> = 135.5, <i>p_{cor}</i> = .39
WM LDSB	<i>M</i> = 5.06, <i>Mdn</i> = 5, <i>SD</i> = 1.16	<i>M</i> = 6.33, <i>Mdn</i> = 6, <i>SD</i> = 1.37	<i>U</i> = 76.0, <i>p_{cor}</i> = .036*
EHI Handedness Quotient	<i>M</i> = 83.33, <i>Mdn</i> = 80, <i>SD</i> = 18.79	<i>M</i> = 89.44, <i>Mdn</i> = 95, <i>SD</i> = 15.52	<i>U</i> = 128.5, <i>p</i> = .27
Music Practice (years)	<i>M</i> = 4.22, <i>Mdn</i> = 0, <i>SD</i> = 7.33	<i>M</i> = 6.56, <i>Mdn</i> = 0, <i>SD</i> = 9.33	<i>U</i> = 145.0, <i>p</i> = .54
Gaming (years)	<i>M</i> = 9.83, <i>Mdn</i> = 0, <i>SD</i> = 11.90	<i>M</i> = 6.31, <i>Mdn</i> = 0, <i>SD</i> = 9.92	<i>U</i> = 173.0, <i>p</i> = .72
CPT 3™ HRT	<i>M</i> = 52.22, <i>Mdn</i> = 52, <i>SD</i> = 9.18	<i>M</i> = 49.56, <i>Mdn</i> = 48, <i>SD</i> = 7.02	<i>t</i> (34) = 0.98, <i>p_{cor}</i> = .39
Omissions	<i>M</i> = 46.83, <i>Mdn</i> = 46, <i>SD</i> = 4.81	<i>M</i> = 46.17, <i>Mdn</i> = 45, <i>SD</i> = 3.73	<i>U</i> = 193.5, <i>p_{cor}</i> = .39
Commissions	<i>M</i> = 47.83, <i>Mdn</i> = 46, <i>SD</i> = 5.67	<i>M</i> = 51.61, <i>Mdn</i> = 50, <i>SD</i> = 9.71	<i>t</i> (34) = -1.42, <i>p_{cor}</i> = .39
Preservations	<i>M</i> = 45.67, <i>Mdn</i> = 45, <i>SD</i> = 1.28	<i>M</i> = 47.28, <i>Mdn</i> = 45, <i>SD</i> = 5.50	<i>U</i> = 135.0, <i>p_{cor}</i> = .39
SSI-4%SS	<i>M</i> = 3.72, <i>Mdn</i> = 3, <i>SD</i> = 3.88		

STM LDSF = raw score of Short-term Memory, as measured by Longest Digit Span Forward (Gignac & Weiss, 2015; Wechsler, 1981); **WM LDSB** = raw scores of Working Memory, as measured by Longest Digit Span Backward (Gignac & Weiss, 2015; Wechsler, 1981); **EHI** = Edinburgh Handedness Inventory Handedness Quotient by percent (Oldfield, 1971); **Conners CPT 3™** = Conners’ Continuous Performance Test Third Ed. (Conners, 2014); **HRT** = Hit Reaction Time on measure of sustained attention, in T-score conversion of mean reaction time is based on the sample mean and sample standard deviation of normative sample of 1400 cases (Conners CPT 3™); **Omissions** = T-score of errors by missed targets on measure of sustained attention (Conners CPT 3™); **Commissions** = T-score of errors by incorrect response on measure of sustained attention (Conners CPT 3™); **Perseverations** = T-score of responses made in less than 100 ms following the presentation of a stimulus; **SSI-4** = Stuttering Severity Instrument Fourth Edition (Riley, 2009); **%SS** = percent syllables stuttered, averaged across reading and conversation samples from the SSI-4.

* *p* < .05 (significance of two-sample test results), *p_{cor}* = significance following FDR correction (Benjamini & Hochberg, 1995).

2. Material and methods

2.1. Participants

Across two groups, 18 AWS (4 female) and 18 ANS (5 female) volunteered to participate in the study. One additional female ANS was excluded from the final analysis due to a longer time interval between their two sessions of participation. All participants were right-handed (Oldfield, 1971), and none reported a history of any health, neurological, physical or uncorrected sensory concerns that could influence motor performance, e.g., sleep disorders, upper-limb injury, and/or developmental, psychiatric or neurological disorders. Written informed consent was obtained from all participants before participation, in accordance with the approved research protocol by the University of Toronto's Research Ethics Board.

All AWS self-identified as persons who stutter and reported a childhood onset of developmental stuttering. Stuttering severity was assessed using the Stuttering Severity Index (SSI-4; Riley, 2009), with results ranging from very mild to severe. On the SSI-4 reading and conversational speech tasks, the percent syllables stuttered were independently scored by the first and last authors on a subset of five participants. The calculated intraclass correlation coefficients, ICC (3,1) (Shrout & Fleiss, 1979) showed good absolute agreement on reading scores of percent syllables stuttered (0.86) and excellent absolute agreement on conversation scores of percent syllables stuttered (0.95).

Practice of a musical instrument and use of video games have been found to influence motor learning across various measures (Krings et al., 2000; Tucker et al., 2016); thus, all participants provided details of their music practice and video gaming history (i.e., years, frequency, and recency of practice), as part of an intake questionnaire. Cognitive capacities and processing abilities were measured in areas of Short-Term Memory (STM) by Longest Digit Span Forward (LDSF) and Working Memory (WM) by Longest Digit Span Backward (LDSB), using a variation of the Wechsler Adult Intelligence Scale-Revised (WAIS; Wechsler, 1981), as well as sustained attention on the Conners Continuous Performance Test (CPT-3™; Conners, 2014). AWS and ANS participants were not found to differ across any measures, except on that of WM. Table 1 provides a summary of participants' scores by group means and their difference, as estimated by Mann-Whitney U and t-tests for independent samples. The false discovery rate among six cognitive measures, including two comparisons of memory (STM and WM) and four of attention (Hit Reaction Time, Omissions, Commissions, and Perseverations on the CPT-3™), was controlled for through application of the Benjamini and Hochberg procedure (1995).

2.2. Experimental paradigm

Participants' explicit motor learning abilities were measured by use of the FOS task, on one of two five-element sequences of finger-to-thumb opposition movements, as described in previous research (Dorfberger et al., 2012; Karni et al., 1995, 1998; Korman et al., 2007, 2017). Each sequence element involved the movement of a finger to make contact with the thumb of the same hand, ranging from the index finger numbered 1 and the little finger numbered 4 (see Fig. 1).

One of two sequence variations (4–2–3–1–4 or 4–1–3–2–4) was visually instructed to the participant via pre-recorded video demonstration and was to be completed by use of their left (non-dominant) hand. Participants practised the sequence while sitting upright with their left forearm resting on the table at which they were seated. In this adaptation of the FOS task, participants were shown the sequence on a 14" computer screen (Dell Latitude with Intel® Core™ i5–6200 U processor at 2.30 GHz), placed on the table before them. The visual introduction involved video demonstration of a left hand performing the task. After viewing the video and imitating the presented finger movements to familiarize themselves with the sequence, participants were asked to repeat the sequence three times in succession. There were no restrictions on how many times participants could watch the instruction and try out the sequence. However, only after the sequence could be completed three successive times without error could participants then progress to the first practice block (Korman et al., 2007, 2017). Participants had full view of their hand while completing the task, with visual feedback of their own performance afforded throughout blocked practice.

Once familiarization had been completed, participants were instructed to perform the FOS sequence as many times and as accurately as possible across 20 blocks of 30-seconds. Between each block, 30-second breaks were taken by all participants, with a longer break of approximately two minutes prescribed between blocks 10 and 11. The participants were encouraged to ignore any errors during practice and continue with the correct sequence. However, if a participant was unable to immediately proceed with the correct sequence or reported not being able to remember it, the practice block was ended and the participant was provided with the visual example again, after which the practice block was restarted. In addition to the prescribed break after 10 blocks, participants were informed that they could extend their breaks if their hand felt strained by the task. No break extensions were requested by any of the



Fig. 1. Finger to thumb opposition sequencing movements for the sequence 4–2–3–1–4.

participants.

After completing their first session involving 20 blocks of practice, participants were asked to return approximately 24 h later, for a second practice session. The time interval between the last practice block in session one and the first testing block in session two did not significantly differ between AWS (mean = 23.7 ± 0.9 h) and ANS (mean = 23.42 ± 0.8 h) groups ($t(34) = 0.973, p = .34, d = 0.324$). In session two, the first block was used to test for sequence consolidation. Participants were not informed in advance about the consolidation test or additional practice of the task on the second day, but only that additional information would be collected and/or tasks completed. All participants were encouraged to rest their hand following their first practice session, so as to discourage additional practice without explicitly being instructed to do so. The consolidation block and additional practice was then carried out the following day across five blocks of 30 s each, again with 30-second breaks between each block.

Participants' performance of the FOS task was recorded by video camera (JVC Everio 40x Optical Zoom Camcorder) during both sessions. Participants rested their hand on the surface in front of them, with the video camera positioned above and at a slight side angle, so that there was a clear view of the participant's full hand, including their palm and finger movements. The outcome measures of sequencing speed and errors were scored offline by the first author, after the experimental sessions. In accordance with previous studies, on-line learning gains were evaluated from within-session increases in sequencing speed and accuracy, whereas off-line gains were measured by between-session gains, from end of session one to the beginning of sessions two (Karni et al., 1995; Korman et al., 2017).

2.3. Statistical analysis and modelling

Performance on the FOS task was measured in terms of sequencing speed by the number of correct sequences completed, and sequencing accuracy by the number of sequencing errors made, during each 30-second block (Korman et al., 2017), across a total of 25 blocks (20 blocks on day one and 5 blocks on day two). The repeated measures of sequencing speed and accuracy were analysed using separate mixed-effects model approaches, using General Linear Models (GLMs) (Zeileis et al., 2008) in R Studio version 4.1.0 (The R Foundation for Statistical Computing, 2021). As calculated by count of correct sequences produced by each participant in each block, sequencing speed was modelled by GLMs with a Poisson distribution, using the `glm()` function with non-transformed data (Chambers & Hastie, 2017) from the "stats" package (R Core Team, 2021). Sequencing accuracy was high overall, with few errors incurred by participants. Analysis of sequencing errors was modelled using GLMs with negative binomial distribution, using the `glm.nb()` function from the "MASS" package (Ripley et al., 2019), to account for over-dispersion of the data (Green, 2021).

In each model, Block 20 was set as the reference criterion to estimate differences in within-session performance (Blocks 1–19), as a between-session effect of consolidation (Block 21), and in extended practice on day two (Blocks 22–25). The factors of Group and Participant were included as fixed and random effects, respectively. The factor of Sex was also evaluated as a potentially significant predictor in the models, as previous research has found this to be an explanatory variable of group differences in motor sequencing performance (Dorfberger et al., 2009; Höbler et al., 2022; Lissek et al., 2007). The predictive values of the fixed effects were compared across GLMs by ANOVA and Chi-squared tests in R (Bates, 2005). Model comparison did not reveal a significant difference between the GLMs analysing Speed with or without the inclusion of Sex as factor ($X^2(50, N = 38) = 29.30, p = .99$). A slightly lower Akaike Information Criterion (AIC) indicated a comparatively better fit of the GLM including the factor of Sex ($AIC = 4699.5$) than in the model without this factor ($AIC = 4770.2$), and, therefore, sequencing speed was analysed across separate GLM models to explore the potential influence of Sex on motor sequence learning. Likelihood ratio tests of Negative Binomial Models for number of sequencing errors did not reveal a better fit for either model with the inclusion of Sex as factor ($X^2(800, N = 36) = 62.50, p = .11$), but the Analysis of

Table 2

Correlation coefficients between measures of On-line Sequence learning, Off-line Sequence learning, Short-term Memory, Working Memory, Sustained Attention, years of Music practice and Gaming experience per group.

Measure	Correlation Coefficient	Off-line Sequences	STM LDSF	WM LDSB	CPT-3 HRT	Music	Gaming
AWS participants		<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 6	<i>n</i> = 8
On-line Sequences	<i>Spearman's rho</i>	-0.619	0.058	0.109	-0.270	0.462	0.585
	<i>adjusted p-value</i>	.036 *	.90	.80	.49	.53	.38
Off-line Sequences	<i>Spearman's rho</i>		-0.266	-0.150	-0.006	-0.577	-0.817
	<i>adjusted p-value</i>		.49	.74	.98	.49	.05
ANS participants		<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 18	<i>n</i> = 7	<i>n</i> = 8
On-line Sequences	<i>Spearman's rho</i>	-0.309	0.110	0.221	-0.309	0.071	0.476
	<i>adjusted p-value</i>	.56	.78	.69	.56	.88	.56
Off-line Sequences	<i>Spearman's rho</i>		-0.147	-0.093	0.105	0.901	-0.347
	<i>adjusted p-value</i>		.78	.78	.78	.036 *	.69

On-line Sequences = mean number of correct sequences gained during the first day of practice (Block 20 – Block 1); **Off-line Sequences** = mean number of correct sequences gained or lost between practice sessions (Block 21 – Block 20); **STM LDSF** = raw score of Short-term Memory, as measured by Longest Digit Span Forward (Gignac & Weiss, 2015; Wechsler, 1981); **WM LDSB** = raw scores of Working Memory, as measured by Longest Digit Span Backward (Gignac & Weiss, 2015; Wechsler, 1981); **Conners CPT 3TM HRT** = Hit Reaction Time T-score on measure of sustained attention on the Conners' Continuous Performance Test Third Ed. (Conners, 2014), where T-score is the conversion of mean reaction time based on the sample mean and sample standard deviation of 1400 normative cases; **Music** = mean number of years of music practice reported by those with > 0 years practice; **Gaming** = mean number of years of video gaming experience reported by those with > 0 years experience. * $p < .05$ = significance following FDR correction (Benjamini & Hochberg, 1995).

Deviance did reveal a significant predictive value of Sex on performance Accuracy ($X^2(1, N = 36) = 16.35, p < .001$).

Additional measures of STM by longest digit span forward, WM by longest digit span backward, Sustained Attention on the CPT-3™ (Conners, 2014), as well as reported years of Music practice and Gaming experience were collected across all participants. The data were first assessed for normality of distribution by use of Shapiro-Wilk test (Shapiro & Wilk, 1965), which indicated that a significant departure from normality for STM scores among AWS ($W = 0.893, p = .043$) and among ANS ($W = 0.845, p = .007$), as well as for the distribution of WM scores among AWS ($W = 0.831, p = .004$). Therefore, the potential associations between these additional measures and explicit motor sequence learning, as measured by on-line FOS sequencing gains (correct sequences on Block 20 – correct sequences on Block 1) and off-line FOS sequencing changes (correct sequences on Block 21 – correct sequences on Block 20), were estimated through calculation of Spearman's rank correlation coefficients within each group (see Table 2). For years of Music and Gaming experience, not all participants reported practicing a musical instrument or playing video games. Hence, only those participants within each group who reported having Music and Gaming experience (more than 0 years) were included in the calculation of correlation coefficients. The false discovery rate (FDR) of multiple comparisons was controlled for by applying the Benjamini-Hochberg procedure to the correlational results (Benjamini & Hochberg, 1995). Significant relationships were then further analysed for their predictive effect across practice blocks by adding the relevant covariate as a fixed effect to separate GLMs for each group. Across all analyses, a statistical significance level of $p < .05$ was accepted.

3. Results

In their practice of the FOS task, the groups of AWS and ANS started with an average of 11.33 ± 4.56 and 11.89 ± 4.64 sequences produced correctly within 30 seconds at the start of practice (Block 1). Sequencing speeds increased to an average of 21.17 ± 6.56 and 20.78 ± 5.70 correct sequences within 30 seconds by the end of practice on day one (Block 20), for AWS and ANS respectively. Across 20 Blocks of practice on day one, AWS performed a total of 361.67 ± 108.23 correct sequences and ANS a total of 346.61 ± 95.29 correct sequences, on average. Across five Blocks of practice on day two, AWS completed an additional 103.33 ± 30.54 correct sequences and ANS 101.33 ± 27.04 correct sequences, on average.

In the analyses of Sequencing Speed and Accuracy, Block 20 was used as the reference standard in each statistical model. With Block factorized within each GLM, participants' attained Sequencing Speed (number of correct sequences completed in 30 seconds) and number of Sequencing Errors at the end of day one (Block 20) were respectively analysed for effects of on-line practice (comparison with Blocks 1–19), off-line consolidation (comparison with Block 21), and extended practice (comparison with Blocks 22–25). As in previous studies of FOS performance (Korman et al., 2007, 2018), participants incurred few errors across FOS practice blocks, and thus, the results of Sequencing Speed are first reported, followed Sequencing Accuracy below.

3.1. Sequencing speed

In the GLM of Sequencing Speed including Block and Group as fixed effects, the main effect of Block demonstrated clear practice effects of participants' motor sequence performance on day one, with performance Speed during the first half of practice found to differ significantly with end of day performance on Block 20 (Blocks 1–10, all p 's $< .05$). Changes in the number of correct sequences completed within 30 s were not found to be significant on any other Block during the first practice session (Blocks 11–19, all p 's $> .05$)

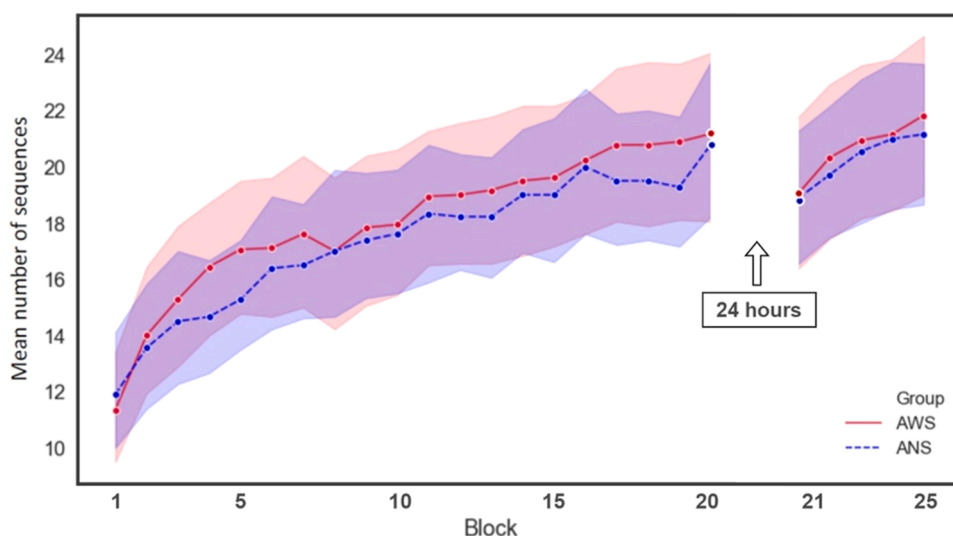


Fig. 2. Performance speed by mean number of correct sequences completed on the FOS task by AWS (red line) and ANS (blue dash) participant groups, on day one (Blocks 1–20) and day two (Blocks 21–25) of explicit motor sequencing practice. Coloured bands indicate 95% confidence intervals of performance speed for each group.

or on day two of practice (Blocks 22–25, all p 's > .05). Although the participants' Sequencing Speed had decreased slightly at the start of practice on day two, the main effect of Block 21 was not significant ($b = -1.782$, $SE = 1.453$, $z = -1.227$, $p = .22$). This showed that performance gains attained by the participants during the first practice session were preserved in the second session. As can be seen in Fig. 2, speed of performance, as measured by mean number of correct sequences produced by each group, was observed to increase across the two days of practice.

The main effect of Group on Sequencing Speed was not significant ($b = 0.257$, $SE = 2.199$, $z = 0.117$, $p = .91$), indicating no difference between AWS and ANS in motor practice by the end of day one (Block 20). The fixed effects of Group and Block did not significantly interact at any point of practice on day one or day two (Group x Blocks 1–19, 22–25, all p 's > .05), nor did they interact in terms of consolidation (Group x Block 21: $b = 0.223$, $SE = 2.052$, $z = -0.109$, $p = .91$). These results indicated no differences between the Groups in their rates of motor sequence learning.

In the GLM including Sex, along with Block and Group as fixed effects, the main effect of Sex was not found to be significant (Sex: $b = 1.481$, $SE = 3.512$, $z = 0.422$, $p = .67$), indicating no differences between male and female participants in Speed of sequencing performance. As a predictor, Sex did not interact with Group ($b = -0.014$, $SE = 5.16$, $z = -0.003$, $p = .998$) and, thus, did not have a mediating effect on potential group differences. Overall, no significant interaction effects between the factors of Block, Group, or Sex were found to predict performance Speed at any stage of practice.

3.2. Sequencing errors

Similar to previous reports (Korman et al., 2017, 2018), the AWS and ANS participants in this study incurred few errors while performing the FOS, resulting in high overall performance accuracy across practice on day one (AWS: Mean = 0.25 ± 0.21 errors per block; ANS: Mean = 0.35 ± 0.41 errors per block), as well as on day two (AWS: Mean = 0.12 ± 0.16 errors per block; ANS: Mean = 0.28 ± 0.34 errors per block). Despite high variability within the groups, Levene's test revealed equal variance between the mean numbers of errors produced by AWS and ANS on day one ($p = .48$) and on day two of practice ($p = .21$).

The GLM of Sequencing Errors included Block and Group as fixed effects, and Participant factor as random intercept. With the reference criterion of performance set for Block 20, there was no significant change in the number of errors incurred during practice on day one, as would be indicated by a main effect of Block (Blocks 1–19, all p 's > .05). When evaluating consolidation of practice gains on the first block of day two, performance accuracy was not found to change significantly from Block 20 on day one to Block 21 on day two (Block 21: $b = 0.198$, $SE = 0.007$, $z = 0.003$, $p = .998$), or with additional practice on day two (Blocks 22–25, all p 's > .05). Overall, performance accuracy, as measured by mean number of sequencing errors for each group, was seen to vary across sessions (as seen in Fig. 3).

There was no significant main effect of Group on the number of sequencing errors produced ($b < 0.001$, $SE < 0.001$, $z = 0.000$, $p = 1.00$), indicating equivalent accuracy between AWS and ANS at the end of practice on day one. There was also no significant main effect of Sex on sequencing errors ($b = 0.194$, $SE = 0.007$, $z = 0.003$, $p = .998$), indicating no difference between male and female participants. No significant interaction effects between factors of Block, Group, or Sex were found.

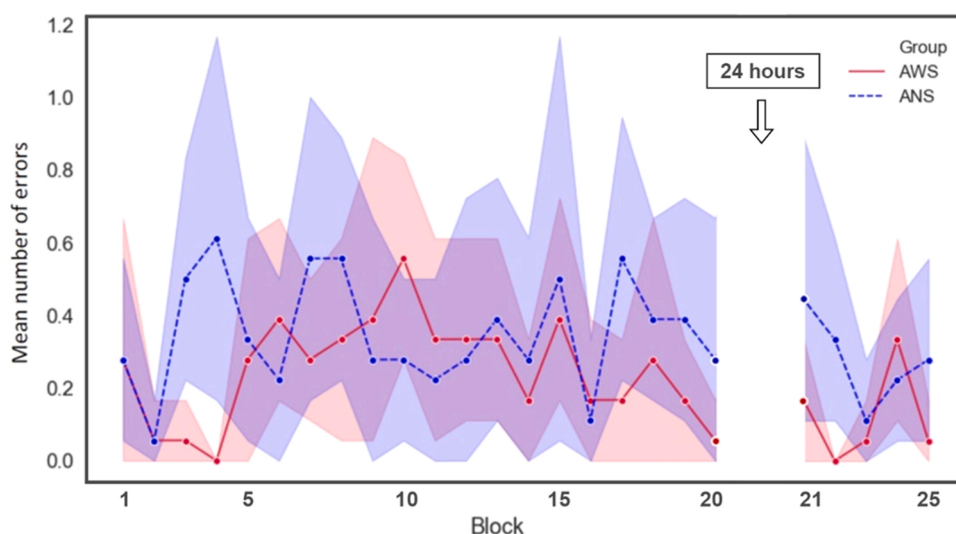


Fig. 3. Performance accuracy by mean number of FOS sequencing errors produced by AWS (red line) and ANS (blue dash) participant groups, on day one (Blocks 1–20) and day two (Blocks 21–25) of explicit motor sequencing practice. Coloured bands indicate 95% confidence intervals of performance accuracy for each group.

3.3. Additional measures

3.3.1. Short-term and working memory

The investigation of mean group differences on additional measures, as summarised in Table 1, revealed no significant differences between AWS and ANS. WM scores were found to be significantly lower among AWS than ANS overall ($U = 76.0, p_{cor} = .036$). Calculation of Spearman's correlation coefficients was carried out to investigate the association between STM and on-line as well as off-line FOS performance, and between WM and on-line as well as off-line FOS performance, respectively. On-line FOS performance was derived from the difference or gains in number of correct sequences completed between Block 1 and Block 20, while off-line FOS performance was indicated by the difference in number of correct sequences completed between Block 21 and Block 20. Neither STM nor WM scores were found to correlate with on-line or off-line FOS sequencing performance for either AWS or ANS (see Table 2).

3.3.2. Sustained attention

Measures of sustained attention were collected on the Conners CPT-3 (Conners, 2014) and revealed no significant differences between AWS and ANS participants on the standardized scores of Hit Reaction Time (HRT), or of errors by omission, commission, or perseveration (as listed in Table 1). Calculation of Spearman's rank correlation to assess the association between participants' sustained attention, as measured by HRT scores, and on-line FOS sequencing gains showed a non-significant, weak negative correlation for both AWS ($r_s(16) = -0.27, p_{cor} = .49$) and ANS ($r_s(16) = -0.31, p_{cor} = .56$). These associations were not further analysed.

3.3.3. Music and gaming experience

The AWS and ANS groups did not significantly differ in years of reported music practice or video gaming (see Table 1). For AWS who reported having experience of practising a musical instrument, a non-significant correlation between their years of Music practice and on-line Sequencing gains was found ($r_s(4) = 0.46, p_{cor} = .53$), as well as a non-significant correlation between Music practice and off-line Sequencing changes ($r_s(4) = -0.58, p_{cor} = .49$). For ANS with Music experience, no correlation was found between their years of Music practice and on-line Sequencing gains ($r_s(5) = 0.07, p_{cor} = .88$), while the positive correlation between their Music practice and off-line Sequencing changes was significant ($r_s(5) = 0.90, p_{cor} = .036$).

Although only one of the above correlations remained significant following FDR correction, the potentially differential association of music experience with explicit motor learning between AWS and ANS was investigated by further statistical modeling. For the subset of participants who reported playing a musical instrument, years of Music practice was included as a fixed effect in a GLM of Sequencing Speed. Music experience was not found to be a significant predictor of FOS performance for these participants overall (Music: $b = -0.172, SE = 0.374, z = -0.462, p = .64$); neither was the interaction between factors of Music and Group significant (Group x Music: $b = 0.059, SE = 0.544, z = 0.109, p = .91$).

Among the AWS participants who reported having video Gaming experience, non-significant correlations between their years of Gaming and on-line Sequencing gains ($r_s(6) = 0.59, p_{cor} = .38$) and with their off-line Sequencing ($r_s(6) = -0.82, p_{cor} = .05$) were found. For ANS participants with video Gaming experience, this was not found to significantly correlate with either their on-line Sequencing gains ($r_s(6) = 0.48, p_{cor} = .56$) nor with their off-line Sequencing Speeds ($r_s(6) = -0.35, p_{cor} = .69$).

To investigate its potential influence on explicit motor sequence learning, years of Gaming was introduced as a fixed effect in GLM analyses of Speed on the FOS among the subsets of AWS and ANS participants who reported having Gaming experience. Years of Gaming were found to significantly predict FOS performance among these participants overall (Gaming: $b = 0.451, SE = 0.204, z = 2.212, p = .027$). However, the interaction between factors of Gaming and Group was not significant (Group x Gaming: $b = -0.045, SE = 0.436, z = -0.103, p = .92$), and was not further investigated.

4. Discussion

In our investigation of explicit motor learning in adults with persistent developmental stuttering, we found that the variables of sequencing speed and accuracy of self-paced finger movements did not indicate any differences between adults who do and do not stutter – either during practice or in consolidation of learning. Specifically, both groups of participants made significant gains in their speed of finger-sequencing performance, as measured by number of correct sequences completed per practice block, on the first day of practice and showed low error production throughout. Thus, participants demonstrated successful acquisition of a new motor skill through its increasingly fluent and efficient execution, without deterioration of sequence accuracy (Friedman et al., 2022). The most significant gains were made by both groups in the first half of their first practice session, during which AWS and ANS both demonstrated fast learning of the finger-to-thumb opposition sequences (FOS). Although a slight decrease in speed of performance on the FOS task was found between the last practice block on day one and the first block on day two, this change was not significant and indicated a relative stabilization of sequencing performance during the 24-hour period between practice sessions.

4.1. Explicit motor sequence learning

The findings from the current investigation fall in line with those from recent studies of explicit motor learning in AWS and ANS. By use of a computerised finger tapping task, in which one of the same five-element sequences was applied as was in the current study, Korzeczek and colleagues (2020) found that AWS and ANS did not differ in the speed or accuracy of their finger-sequencing performance, following a practice session of 160 cued sequence repetitions. The groups also demonstrated similar retention of their finger-sequencing gains following a 24-hour interval. Unlike the practice conditions provided by Korzeczek et al. (2020), however, each

sequence repetition was not cued in the current study, and our participants also completed more than twice the number of sequence repetitions, on average. Furthermore, our participant groups did not differ in their performance on the first or last block of FOS practice, while the AWS participants in the former study were found to produce fewer correct sequences at baseline (Korzeczek et al., 2020). The authors suggest that the significant difference at baseline and then similar performance post-practice would indicate a greater learning benefit to the AWS than to the ANS participants in their investigation (Korzeczek et al., 2020). Greater gains made by AWS during on-line learning may also suggest that the participants in this group had more scope for improvement during practice. Similarly, in an earlier study of finger sequence learning by Bauerly and De Nil (2015), AWS demonstrated performance improvements that spanned across a greater number of practice blocks than ANS, while the latter group were found to reach a plateau earlier in their motor sequence learning. In the current study, both AWS and ANS demonstrated fast learning in the first half of their first practice session, which coupled with a low error rate seen across both groups, may indicate saturation of early learning before the end of their first practice session (Ghilardi et al., 2009).

Comparable to the current findings, Masapollo et al. (2021) reported similar motor learning trajectories across their AWS and ANS participant groups, when practising a verbal motor sequencing task under explicit conditions. In their study, participants produced 30 CCVCC nonword sequences 32 times across eight blocks in total, which were equally distributed across two days of practice (Masapollo et al., 2021). The task stimuli also varied in complexity between 15 nonwords containing non-native consonant clusters and 15 containing native consonant clusters. Again, by use of a cued motor learning paradigm, AWS and ANS produced similar motor performance gains on the verbal sequencing task (Masapollo et al., 2021). However, unlike previously reported by Korzeczek et al. (2020), AWS continued to perform sequences more slowly and less accurately than their ANS counterparts after two days of practice; yet, both groups demonstrated similar decreases in neural activation. The authors suggested that comparable decreases in activation reflected corresponding reductions in WM demands and articulatory effort for AWS and ANS, following increased chunking of sequence elements across practice (Masapollo et al., 2021).

Taken together, these findings point towards the benefit of explicit practice conditions to on-line motor sequence learning and retention in AWS (Korzeczek et al., 2020; Masapollo et al., 2021). When practising non-verbal sequences that are five elements in length, not only are similar performance gains made by AWS to those of ANS, but AWS may also be able to compensate for baseline differences by making greater on-line practice gains, when there is increased scope for improvement among participants (Korzeczek et al., 2020). Yet, 32 distributed practice trials may not be sufficient for AWS to catch up with the performance of their ANS counterparts on a verbal motor sequencing task that elicited between-group differences at baseline, particularly when task stimuli vary in complexity and call upon speech production demands (Masapollo et al., 2021). In the current investigation, however, participants completed sufficient practice trials on the FOS task to see on-line performance gains of both AWS and ANS reach saturation or asymptotic levels – a stage of practice that is thought to be critical to the processes of successful memory consolidation and the expression of off-line gains (Hauptmann & Karni, 2002; Hauptmann et al., 2005).

4.2. Task complexity

Although the evidence of comparable motor sequence learning found between the groups in this study coincides with that from similar investigations in motor learning under explicit and extended practice conditions (Korzeczek et al., 2020; Masapollo et al., 2021), differences between the motor sequencing performance of AWS and ANS have previously been reported in investigations of explicit verbal as well as explicit non-verbal sequence learning (Bauerly & De Nil, 2015; Smits-Bandstra, De Nil et al., 2013; Smits-Bandstra, De Nil, Rochon et al., 2006). While performance speed was measured by number of correct sequences produced within a 30-second block, in the current study as well as in Korzeczek et al. (2020), the behavioural measure that has been found to evidence persistent performance differences between groups of AWS and ANS has been that of RT.

Performance differences between AWS and ANS on measures of RT have been well established, most notably by RT delays among AWS on tasks that require an immediate response (for review, see Smits-Bandstra, 2010). Slower RTs have been observed among AWS on both simple and complex RT tasks. While RT differences can diminish with practice on simple, single-response tasks (Smits-Bandstra, Bauerly, Kroll, Gracco, & De Nil, 2010), studies of verbal sequencing (Bauerly & De Nil, 2011; Smits-Bandstra & De Nil, 2009; Smits-Bandstra & Gracco, 2013) as well as finger sequencing skills (Bauerly & De Nil, 2015; Höbner et al., 2022; Smits-Bandstra et al., 2006; Smits-Bandstra, De Nil et al., 2013) have found that slower response times among AWS tend to persist across practice. Motor sequence learning, as measured on serial RT tasks (SRTTs), has been associated with neural activity across cortico-basal ganglia-cerebellar circuits (Doyon et al., 2003; Hikosaka et al., 2002; Janacek et al., 2020; Ungerleider et al., 2002). The cerebellum is thought to be most critical to the early stages of explicit sequence learning (Bernard & Seidler, 2013; Pascual-Leone et al., 1993), the basal ganglia increasingly involved into later stages of motor sequence learning (Doyon et al., 2003; Janacek et al., 2020), and activity of the precuneus seen to be related to RT improvements in sequence learning (Oishi et al., 2005). Differential neurodevelopment and activation in persons who stutter have been found across these regions (Beal et al., 2013; Chang & Zhu, 2013; De Nil et al., 2001; Sitek et al., 2016; Toyomura et al., 2011; Yang et al., 2016), which may play a role in persistent performance differences found in RT and complex sequencing tasks across extended practice.

Two studies of verbal sequence learning under explicit conditions, with practice distributed across two days, have demonstrated the benefits of distributed schedules to motor learning in AWS (Bauerly & De Nil, 2011; Masapollo et al., 2021). In both studies, AWS retained their gains in speed of performance and continued to improve on the second day of practice, but performance differences persisted between AWS and ANS on measures of RT (Masapollo et al., 2021) and sequence duration (Bauerly & De Nil, 2011), despite successful consolidation and continued improvements being made by AWS. When these findings are contrasted with the sequencing speeds attained and retained by participants in the current study and those of Korzeczek and colleagues (2020), this may suggest that

AWS are more susceptible to delays on motor learning tasks that involve externally cued responses, perceptual processing demands, or speech production requirements.

These differential findings in both on-line and off-line performance gains made by AWS, however, also lend support to the critical aspects of sequence complexity and the number of practise trials afforded to participants (Smits-Bandstra, 2010). As reported by Korzeczek et al. (2020), AWS made improvements across a greater number of trials, when practising a five-element sequence, which enabled them to catch up with the finger sequencing speeds of ANS. However, Bauerly and De Nil (2015) found that when practice of a ten-element sequence was interspersed with a dual task, the response times attained by AWS during practice were not retained 24 hours post-practice. Smits-Bandstra and Gracco found that, although AWS made greater on-line sequencing gains than ANS during initial practice (Smits-Bandstra & Gracco, 2013), AWS were unable to retain gains in RT at one-week follow-up (Smits-Bandstra & Gracco, 2015), when this involved an eight-element verbal sequence practiced under implicit conditions. Therefore, in addition to the potential functional difficulties that may be posed by a speech production task (Guadagnoli & Lee, 2004), both the length and complexity of the sequence, as well as the conditions of practice, may influence the time course of motor sequence learning for AWS. The introduction of a motor task that is concurrent or consequent to practice can interfere with the process of motor memory consolidation (Korman et al., 2007; Korman, Flash, & Karni, 2005), which may take longer in AWS when acquiring lengthier or more complex sequences than those in the current investigation (Bauerly & De Nil, 2011; Smits-Bandstra & De Nil, 2009; Smits-Bandstra, De Nil et al., 2013).

Finally, an important distinction between the structure of the finger sequences used in the current investigation and those that have elicited between-group differences in previous studies (Bauerly & De Nil, 2011, 2015; Höbler et al., 2022; Smits-Bandstra & De Nil, 2009; Smits-Bandstra & Gracco, 2013, 2015; Smits-Bandstra et al., 2006; Smits-Bandstra, De Nil et al., 2013) pertains to the length of the sequence and its motor programming requirements. The acquisition of complex motor sequences involves a process of organising the sequence into its smaller parts, or chunks, to facilitate storage, retrieval and more efficient sequential movement execution (Bo & Seidler, 2009; Cowan, 2001; McKone, 1995; Verwey, 2001, 2003). This process most often involves the grouping of three- or four-elements into subsequences or chunks (Bo & Seidler, 2009; Cowan, 2001; McKone, 1995), and is also reflected in the programming of speech movements into frequently produced phonological units or syllabic chunks (Bohland et al., 2010; Guenther, 2016; Segawa et al., 2015; Segawa et al., 2019).

Chunking can be observed in the emergence of longer inter-element response times that represent segment boundaries, as well as shorter inter-element response times that reflect a strengthening of associations within chunks (Bo & Seidler, 2009; Sakai et al., 2004; Sakai et al., 2003). The process of chunking has been found to correlate with WM (Bo & Seidler, 2009), and to be functionally dependent upon the basal ganglia (Boyd et al., 2009; Graybiel, 1998). Previous studies of finger sequence learning have found delays among male AWS in their shortening of inter-element response times for chunk formation (Smits-Bandstra, De Nil et al., 2013), as well as in their higher-order processing of probabilistic three-element structures that facilitates sequence-specific learning (Höbler et al., 2022). While sequences involving six or more elements have been found to be programmed as shorter chunks of the overall sequence (Bo & Seidler, 2009; Bo, Borza et al., 2009; Verwey, 2001, 2003), the five-element FOS sequence can be acquired as a sequence-specific chunk in itself (Rozanov et al., 2010). In the current study, although the participant groups were found to differ on the measure of WM, this was not found to correlate with or predict their on-line or off-line motor sequence learning gains, and may not have been called upon during their explicit practice of the five-element FOS sequence.

4.3. Focus of attention

Beyond the parameters of sequence length and complexity, motor sequencing tasks can differ in their attentional requirements and whether the sequences are being learned explicitly or implicitly (Bo & Seidler, 2009; Fletcher et al., 2005; Hazeltine et al., 1997; Howard et al., 2004; Nissen & Bullemer, 1987; Seidler et al., 2012). On the FOS task, explicit instruction and the provision of sequence information in a visual format draws the attention of the participant to what is being learned. However, by use of the SRTT or its variations, participants may demonstrate motor sequence learning in improved speed and accuracy of sequencing performance without being aware of, or their attention having been drawn to the sequential structure of the task (Fletcher et al., 2005; Howard & Howard, 1997; Howard & Howard, 2001; Janacek et al., 2012; Nemeth et al., 2013; Nissen & Bullemer, 1987; Song et al., 2007).

Both a verbal form of the SRTT and a nonverbal form of the alternating serial reaction time (ASRT) task have been used to investigate implicit motor learning in AWS. Smits-Bandstra and Gracco (2013, 2015) found that both AWS and participants with Parkinson's Disease made fewer early performance gains in general learning, as well as showing reduced implicit sequence learning and off-line consolidation when compared to ANS, in performing an eight-element verbal sequencing task without awareness of the sequence. Höbler et al. (2022) found reduced sequence-specific learning among male AWS across two sessions of implicit finger sequence learning on a ten-element ASRT task, when compared to the on-line sequence-specific gains made by their ANS counterparts.

Implicit sequence learning, as well as the chunking and automatization of sequences, has been found to be functionally reliant on cortico-basal ganglia thalamocortical circuits (Alm, 2021; Doyon et al., 2003; Janacek et al., 2020; Smits-Bandstra & De Nil, 2007; Smits-Bandstra & Gracco, 2015). The functioning of this particular circuitry is thought to be impaired in individuals who experience developmental stuttering, and said to contribute to difficulties in the fluent execution of internal speech motor programs (Alm, 2021; Chang & Guenther, 2020; Smits-Bandstra & De Nil, 2007; Smits-Bandstra & Gracco, 2015). While similar or superior motor sequencing gains in explicit verbal and non-verbal sequence learning have recently been reported in AWS (Korzeczek et al., 2020; Masapollo et al., 2021), the processes and neural systems supporting motor sequence learning under implicit conditions may be implicated in persons who stutter (Höbler et al., 2022; Smits-Bandstra & Gracco, 2013, 2015).

In addition to the distinctions in awareness between motor tasks that are acquired explicitly or implicitly, the performer's focus of

attention, whether this is external or internal, can also influence performance outcomes on the motor learning task. Studies have demonstrated that when the individual's attention is externally focused on the effects of their movement, performance accuracy, efficiency, and consistency improve to a greater degree than when movements are practiced with an internal focus, such as concentrating on the movements themselves (Shea & Wulf, 1999; Wulf, 2013; Wulf et al., 2001). In the current study, we examined motor learning whereby participants were explicitly instructed on the sequence of finger-to-thumb opposition movements to be learned, without being required to respond to any external stimuli or cueing. Visual feedback of their own performance was not withheld, and so participants had full view of their finger movements and could make adjustments, as they deemed necessary. Thus, in contrast to investigations of implicit learning or studies using RT tasks, the participants' attention was internally focused on their own movements, without the distraction of extraneous variables.

A similar focus is often adopted within the clinical setting, whereby fluency enhancing speech behaviours are instructed or modelled in an explicit manner, and are consequently performed with an internal focus of attention. According to the principles derived from motor learning research, however (Shea & Wulf, 1999; Wulf et al., 2001; Wulf, 2013), in order for these speech behaviours to be successfully transferred beyond this setting and generalised across a range of communication scenarios, an externalised focus of attention may be more beneficial. Thus, common clinical practices of explicit instruction and internalised focus of attention may not adequately facilitate the development of more implicit learning processes that maintain complex speech skills in the long-term, including implicit speech motor adaptation processes which have also been found to be impaired and may warrant additional support in children and adults who stutter (Kim & Max, 2021). The conditions of speech motor skill practice are of particular relevance to persons experiencing persistent developmental stuttering when considering success that may be achieved within the clinical setting, while challenges to long-term maintenance and issues of relapse are reported among by children and adults who stutter following fluency treatment (Craig, 1998; Hancock & Craig, 1998; Silverman, 1981; Wingate, 1964).

4.4. Behavioural correlates of explicit motor learning

As part of our investigation into explicit motor sequence learning in adults with persistent developmental stuttering, we explored the potential influence of WM, sustained attention, as well as prior practice of a musical instrument or of video games among participants. Previous studies have pointed towards the influence of WM capacities on motor sequence learning under explicit conditions of practice, in particular (Bo & Seidler, 2009; Bo, Borza et al., 2009; Jongbloed-Pereboom et al., 2019; Seidler et al., 2012). Although differences in participants' longest digit span backward (LDSB), as a measure of WM, were found to be statistically significant, these scores did not correlate with their on-line or off-line motor sequencing performance gains on the FOS task. Difficulties in sustained attention have also previously been found to influence both on-line performance accuracy as well as between-session consolidation of explicit motor sequencing skills (Adi-Japha et al., 2011; Korman et al., 2017). The participant groups in the current study were not found to differ across indices of sustained attention, as measured on the Conners CPT-3™ (Conners, 2014), and their response performance on this measure did not correlate with either their on-line or off-line explicit motor sequencing gains.

Additionally, measures of prior musical practice and video gaming were collected by self-reported years of experience. When compared to adults without musical proficiency, the long-term motor practice of musicians has been shown to reduce activation in cortical areas which relate to a decreased effort necessary for motor performance of a finger-sequencing, as well as relating to their level of perceived task complexity or difficulty (Krings et al., 2000). Imaging research has also found that individuals who play action video games on a regular basis show reduced motor-related preparatory activity in occipital regions and the cerebellum while completing motor learning tasks, when compared to individuals who do not play video games (Gorbet & Sergio, 2018). Video gaming experience has also been found to benefit not only motor skill proficiency, but the development of attention skills (Dye et al., 2009), WM, and cognitive performance in older adults (Basak et al., 2008), as well as sensory and temporal processing (Donohue et al., 2010; Sinnott et al., 2020).

Among the participants in the current study who had previous musical experience, the association between years of practising a musical instrument and FOS sequencing gains was only found to be significant in terms of off-line performance differences found among ANS with music experience. However, across both AWS and ANS participants with video gaming experience, years of gaming was found to predict their speed of sequencing on the FOS task. Overall, this suggests a potential benefit of motor skills proficiency, as a result of video gaming, to participants completing the motor learning task in the current investigation. Although we did not explore whether individual strategies were employed in participants' performance of finger-to-thumb opposition movements, when considering the implications of previous findings of limited complex motor skill acquisition and implicit learning in AWS, in particular for the proceduralization of motor skills, evidence to suggest a positive influence of general motor proficiency may be interpreted as encouraging.

The potential generalizability and differential benefits of general motor abilities may lend itself to motor learning in other contexts, such as in the clinical setting (Hands et al., 2018). When considering the explicit nature of instruction in a therapeutic context, fluency strategies may be acquired under explicit and attention-focused conditions early on in the treatment process. This focused approach to motor practice, during which the individual attends entirely to their own bodily movement, may be relatable to the participants' experience of practising the FOS task in this study. Generalizing fluency skills beyond the clinical setting and across communication contexts with reduced attentional demand is of critical importance to successful treatment outcomes, however. When gains are made early in the treatment process, the ability of the client who stutters to reduce their conscious awareness and focused control of fluency-enhancing speech motor skills must be carefully monitored and may require additional support. Whether general motor practice may potentially facilitate bridging the gap between explicit motor learning and the proceduralization of skills is an area worthy of further investigation.

4.5. Limitations and future directions

The current investigation was focused on the explicit motor learning abilities of adults who do and do not stutter across two practice sessions, examining potential group differences in on-line performance as well as in off-line consolidation. We did not investigate the abilities of participants to transfer their motor sequence knowledge, e.g., to another effector (Korman et al., 2003), nor did we look at the specificity of the participants' motor skill, e.g., by transfer to an alternative sequence or modality (Bird & Heyes, 2005; Rozanov et al., 2010). In addition, the automaticity of motor skill, as observed under conditions of interference or increased cognitive demands, e.g., by use of a dual task paradigm (Bauerly & De Nil, 2015; Smits-Bandstra, De Nil, Rochon et al., 2006), was not tested.

Future research into the transfer, generalizability and automaticity of motor skill acquisition among children and adults who stutter may provide further insight into the abilities of these individuals to achieve their treatment goals, when intervention is focused on enhancing fluency through the application of speech motor strategies. Furthermore, there remains a need to evaluate motor skill acquisition among AWS across multi-session practice and at extended follow-up (Karni et al., 1995; Korman et al., 2003), so that the long-term retention and maintenance abilities of those who experience developmental stuttering can be evidenced. As previously noted, this is of particular importance when considering the high rates of relapse that have been reported among those with persistent developmental stuttering (Craig, 1998; Silverman, 1981; Wingate, 1964).

Furthermore, previous research has found sex-based differences in motor performance (Der & Deary, 2009; Lissek et al., 2007), in studies using the FOS task (Dorfberger et al., 2009), as well as between AWS and ANS in their implicit motor learning abilities (Höbler et al., 2022). Although we aimed to match our participant groups on factors of age and sex, the participants in the current study were not balanced for sex within each of the groups. Increased research into sex-based differences that influence motor performance in AWS is also needed, and whether these may reflect underlying neurodevelopmental distinctions, variations in sensorimotor, attentional or supporting processes, or divergent experiential influences on motor skill learning. As in the current report, many studies to date have been under-powered by fewer female participants or have focused on male AWS alone (Bauerly & De Nil, 2011, 2015; Smits-Bandstra & De Nil, 2009; Smits-Bandstra et al., 2006; Smits-Bandstra, De Nil et al., 2013).

The current study found associations between years of video gaming experience and motor sequencing performance on the FOS task among participants. Future research may wish to further explore the generalizability of motor practice across other modalities among individuals who stutter, and how these may benefit developmental as well as treatment outcomes at various stages of the lifespan. Previous research has found benefits of both musical practice and gaming experience across several domains, and may offer interesting opportunities for their application as motor learning support within the therapeutic process (Demers et al., 2021; Latham et al., 2013; Yunusova et al., 2017).

5. Conclusion

Explicit motor learning was not found to differ between AWS and ANS on the finger-opposition sequencing task in this study, either within the first practice session or in the retention of practice gains between sessions. Successful motor sequence learning on the FOS task may indicate that improvements in motor skill performance can be attained within a single practice session, and under conditions of focused attention and explicit awareness. Further research is warranted into the motor learning abilities of children and adults who stutter when multiple sessions of practice are provided, as well as into the transfer and generalizability of motor skills, and their automaticity under more demanding conditions of interference. These may be particularly relevant to the selection of appropriate intervention tasks and treatment goals for individuals who stutter, and may provide further insight into individual abilities to maintain treatment gains beyond the clinical setting and into the longer term.

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Declarations of interest

None.

Data Availability

The authors do not have permission to share data.

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