Implicit motor sequence learning in adults with and without Developmental Coordination Disorder (DCD).

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Abstract

Objectives: Even though individuals who have DCD may have difficulties learning a motor skill, few studies have investigated the mechanisms involved. Understanding these mechanisms and whether individuals with DCD show selective deficits would be of theoretical and practical interest. This study examined implicit motor sequence learning in adults with and without DCD using a serial response time (SRT) task.

Methods and Procedure: Eleven participants with DCD (according to the DSM-5 criteria) and 18 participants without DCD matched for age, gender and handedness completed a version of the serial response time (SRT) task. Following this, a free generation task (FGT) assessed explicit sequence knowledge.

Results: Both groups were able to complete the SRT task and showed comparable accuracy. A *Condition* x *Block* interaction for response time (RT) data during the learning phase was explained by a failure of the DCD group to improve their performance, while the control group showed the typical learning effect of gradually faster RTs. Responses on the FGT revealed that the DCD group also acquired significantly less sequence knowledge than the control group during the task. Controlling for the development of sequence knowledge across the two groups still revealed an implicit learning deficit in the DCD group.

Conclusions: Adults with DCD failed to demonstrate the typical signs of implicit (procedural) learning on an established and influential sequence learning task. In addition, difficulties in acquiring task-related knowledge may point towards multiple difficulties in learning motor skills.

Keywords: Motor Sequence Learning, Implicit, Explicit, DCD, Adults, Free Generation Task

Developmental Coordination Disorder (DCD) is a disorder that affects motor skills and interferes with activities of daily living such as dressing, sports, using a knife and a fork, handwriting (American Psychiatric Association (APA), 2013; Blank et al., 2019) and may continue to adulthood (Cousins & Smyth, 2003; Tal-Saban et al., 2012). Its prevalence is estimated to be around 2-6% (DSM-5, APA, 2013; Lingam et al., 2009). An individual diagnosed with DCD should meet four criteria set by the American Psychiatric Association (DSM-5, APA, 2013). The coordination of motor skills should be below the expected level of the individual's chronological age (Criterion A), should interfere with daily life and impact school activity, play and leisure (Criterion B), should start in the early developmental period (Criterion C) and the deficits in motor skills are not due to a neurological disorder (e.g., cerebral palsy) or visual impairment and cannot be attributed to intellectual developmental disorder (Criterion D) (APA, 2013). However, alongside poor motor skills individuals with DCD may experience problems in other domains of their lives such as academic (e.g., reading and writing), psychosocial (e.g., anxiety, bullying) and emotional (e.g., low self-esteem). These problems may start as young as six years old (e.g., Schoemaker & Kalverboer, 1994) and may continue to later adolescence (e.g., Cleaton & Kirby, 2018; Skinner & Piek, 2001) and adulthood (e.g., Cleaton & Kirby, 2018; Cousins & Smyth, 2003; Hill & Brown, 2013).

While, by definition, individuals with DCD have difficulties with movement, our understanding of any more precise underlying deficits is less clear. For example, while it seems likely that DCD may include problems in learning movement, few studies have examined this issue specifically. Furthermore, should DCD include specific problems with motor learning, what is the nature of these? For example, a distinction that is typically made in understanding motor learning is between *implicit* and *explicit* processes. Here, explicit learning refers to a conscious process which results in the individual knowing what has been learned and can verbalise (declare) this. In contrast, implicit learning refers to skill acquired through practice without awareness (procedural) (Schwarb & Schumacher, 2012). While both components support learning, it is possible for one component to be more affected than the other. Understanding these processes in individuals with DCD would not only be of theoretical interest but could have practical value and drive the development of interventions aimed at optimising function in those affected.

The serial reaction time (SRT) task is a well-established paradigm that has been used in both typical and atypical populations to examine the processes involved in both implicit and explicit motor sequence learning. In this task, spatially congruent manual responses are made to presented visual stimuli. The order of stimulus position is typically presented in a repeating pattern (e.g., a 10 or 12 element sequence) within a block of trials, though participants are not typically informed of this. Commonly, a practice trial or familiarization phase is followed on by the sequence trials and the task finishes with a random (or alternative) sequence block or test blocks. The SRT task may be described as a choice reaction time task and the accuracy and latency of responses are measured. The former indicates an individual's ability to perform the sequence but also their "learning of the visuomotor association, or mapping, between position of the visual cue and the required response" (Robertson, 2007, p.10073). Reduction in response time and increased accuracy in the absence of explicit sequence knowledge indicate implicit learning (Robertson, 2007). More specific, significant reduction in response time should be found either (i) between the first to the last (or test) sequence blocks, or (ii) between the final sequence block with a subsequent random (or alternative sequence block) (Nissen & Bullemer, 1987; Robertson, 2007). However, such reduction may be contaminated by factors such as fatigue, motivation and the fact that an individual may have become aware of the sequence and therefore, developed explicit learning.

To overcome some of these issues, several suggestions have been put forward. For example, researchers are now using more complex sequences known as Second Order Conditional (SOC) sequences (i.e., the position of the target on a specific trial is dependent on the position of the target used in the previous two trials) as their complexity makes awareness far more unlikely. Irrespective of this consideration, awareness of the sequence may still occur and for this reason, other methods to measure explicit sequence knowledge can be used such as explicit questioning (i.e., participants are asked to verbally report on what the goal of the task was and whether they identified a sequence), forced-choice recognition questionnaires (i.e. participants are asked to identify chunks of sequences) and free generation tasks (FGTs) (i.e. participants are asked to reproduce the sequences by pressing the allocated buttons in the keyboard) (for a review see Schwarb & Schumacher, 2012).

To date, three previous studies have examined motor sequence learning in children with DCD using the SRT task, two suggesting a deficit in implicit learning (Blais et al., 2021; Gheysen et al., 2011) and one not (Wilson, et al., 2003). Interestingly, awareness of sequence was only found in a small proportion of children with (i.e., 27.7%) and without DCD (i.e., 25%) in one of the studies (Gheysen et al., 2011) and none in another (Wilson et al., 2003). The inconsistent results may be due to the different methods used to measure motor sequence learning and explicit sequence knowledge. A further challenge in comparing and interpreting different studies is due to the established heterogeneity in the DCD population and differences in sample selections; for example, children with DCD recruited from clinics differ in praxic skill tasks in comparison to children recruited from schools (Sinani et al., 2011). In the SRT tasks conducted to date, Wilson et al. (2003) recruited their children from schools whereas Gheysen et al. (2011) from special needs schools and clinics. However, the differences between the participants with DCD with respect to sample characteristics and the implicit learning tasks applied prohibit a general conclusion about the relationship between deficits of implicit sequence learning and the developmental progression of DCD. Nonetheless, the investigation of motor sequence learning using the SRT task may enhance our knowledge and understanding such deficits that may exist in children and adults with DCD and whether these are independent of developmental and associated symptomatic changes.

To our knowledge, no study to date has examined motor sequence learning using the SRT task in adults with DCD. This study aimed to examine implicit motor sequence learning in adults with and without DCD using a SRT task. It was hypothesised that adults with DCD would show a deficit in implicit motor sequence learning when compared to typically developing adults (Control group). It was also hypothesised that adults with DCD would demonstrate an explicit sequence knowledge measured with the FGT comparable to the Control group.

Method

Participants

Adults with DCD. Eleven participants with DCD (aged from 18 to 61 years old) were recruited from the Disability Services of Higher Educational Institutions in Yorkshire (UK). All participants in this group met the DSM-5 criteria for DCD. A modified three-step procedure previously used for children with DCD was followed (see Sinani et al., 2011). In the first step, information is collected using the Adult Developmental Co-ordination Disorders Checklist (ADC) (Kirby et al., 2010) (Criteria B and C).

For those individuals where this step highlighted ‘likely’ difficulties (total ADC score of 90 and above; indicate ‘likely difficulties’) the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, Brief Form (BOT-2 Brief; Bruininks & Bruininks, 2005) was administered. Only individuals with a standard score below 41 (i.e., below the 18th percentile) in the BOT-2 Brief were included in the DCD group (Criterion A)). According to the manual any individual with a standard score between 31-40 (i.e., 3-17 percentile) demonstrates ‘below average performance’ and with a standard score between 30 or less (i.e., 2 or less percentile) demonstrates ‘well-below average performance’. The same BOT-2 cut-off scores were also used previously to identify adults with DCD by Wilmut et al. (2013).

In the third step, we ensured that Criterion C was met by considering the responses in the subscale A (i.e., as a child questions) of the ADC checklist. The authors do not suggest the cut-off for this subscale and for this reason we calculated the mean of our control group and applied 2 standard deviations above the mean (please note higher scores indicate more problems). Therefore, for an individual to have met Criterion C a score of 25 and above in subscale A was applied. All individuals in our DCD group had a score of 25 and above and therefore, we felt that they met this criterion. All adults with DCD were identified in line with the DSM-5 criteria for DCD, recommendations on identifying adults with DCD (Barnett et al., 2015) and work previously carried out in adults (i.e., Hyde et al., 2019 and Wilmut et al., 2013). Individuals with known or diagnosed neurological damage/impairment, significant learning difficulties, autism, Asperger’s, ADHD or language disorders were excluded (see Table 1).

Adults without DCD (Control). Eighteen participants without DCD (aged from 19 to 56 years old) were recruited from Higher Educational Institutions in Yorkshire (UK) to be matched as closely as possible to the DCD group in terms of age, gender, intelligence and handedness. Individuals were excluded from this comparison sample if their total ADC score was 80 or above (i.e., indicates ‘probable difficulties’), the BOT-2 Brief was at a standard score above 41 (i.e., 18th percentile or above), had known or diagnosed neurological damage/impairment, developmental coordination disorder, significant learning difficulties, autism, Asperger’s, ADHD or language disorders (see Table 1). Two individuals from our control group had a score of 25 and 26 in the ACD A subscale however, the ADCD total score was 78 and 76 and fell within the 54th centile of the BOT-2 Brief respectively. Consequently, we felt confident that these individuals met the criteria and were included in the control group.

Procedure

Each participant was assessed individually in a quiet private room and in a research laboratory in the University. Each participant attended two sessions. In the first session, each participant was assessed against the inclusion and exclusion criteria. This session lasted for about 80 minutes and breaks were given when needed to minimise fatigue. Each participant who met the inclusion and exclusion criteria was asked to attend another session where the Learning (SRT) Task was administered first, followed by the Sequence Knowledge Test (FGT).

Measures

Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, Brief Form (BOT-2 Brief). The only test that can determine the level of motor skills below the level expected for the individuals’ chronological age is the BOT-2 Brief (Bruininks & Bruininks, 2005). The

BOT-2 has been found out to be the most reliable and valid tool for identifying motor coordination in adults (Hands et al., 2015; McIntyre et al., 2017) and has been used in studies carried out in adults with DCD (e.g., Hyde et al., 2019; Wilmut et al., 2013) and for this reason it was used in this study. It is a standardised test with norms for children and youths between the ages of 4 to 21 years old, comprising of four motor-area composites: fine manual control, manual coordination, body coordination and strength and agility. Each composite is subdivided into two subtests. An individual receives a total standard score that can be converted in percentiles. Reliability and validity data are moderate to adequate (Bruininks & Bruininks, 2005).

Adult Developmental Co-ordination Disorders Checklist (ADC). The ADC checklist is a criterion self-reported questionnaire for adults with DCD aiming to measure impact on someone's life. It is consisted of three subscales and examines someone's functioning in various contexts and environments during childhood (Criterion C) and current life (Criterion B). A total score is calculated by combining the scores from all three subscales. A total score of 80 and above signifies 'probable' difficulties whereas a total score of 90 and above signifies a 'likely' difficulty. Reliability and validity data are good to adequate (Kirby et al., 2010).

Raven's Standard Progressive Matrices (RSPM) test – 9-item forms. The RSPM is a 60-item recognised measure of general intelligence. A geometric puzzle with one-piece missing forms each item. An individual completing the test is asked to choose the missing piece from a number of possible answers. Correct answer and response time are recorded. Due to its nonverbal aspect someone's language skills will have no impact on performance (Raven, et al., 1998). To ensure that both groups were matched as closely as possible in intelligence, the two 9-item forms of the RSPM were used. Reliability and validity data are moderate to good (Bilker et al., 2012).

The Wender Utah Rating Scale (WURS). Considering the co-occurrence of attention and motor problems information about attention were obtained using the WURS. The WURS is an adult 61-item questionnaire and provides a retrospective rating for childhood Attention Deficit Hyperactivity Disorder (ADHD). For each question their five possible responses related to the individual's childhood behaviour from which 25 are associated with ADHD. A total score of the ADHD questions of 46 and higher has been shown to identify 86% of patients with ADHD.

Handedness. Handedness was established using the Edinburgh Handedness Inventory (Oldfield, 1971).

Learning task. The experimental task comprised a version of the Serial Response Time (SRT) task (Nissen & Bullemer 1987; Robertson 2007). The task was built and controlled using E-Prime 2 software (www.pstnet.com/e-prime). Four 3cm white-edged square boxes were presented, distributed evenly from left to right (screen locations 1-4) towards the bottom of a computer monitor with a black background (see Fig. 1). Targets were small red filled circles (1cm diameter) and could appear in the centre of any box. Only one target could appear at a time. The participant sat with the monitor in their mid-sagital plane, the four fingers of their dominant hand resting on the V, B, N and M keys of a standard computer keyboard that was placed directly in front of the monitor. The participant's task was to respond to targets presented as quickly and as accurately as possible, in a spatially aligned manner. For example, the correct response for a target appearing in location 1 was 'V', for location 2 it was ‘B’ and so on. Targets were removed from the screen when a response was registered. The following target then appeared after a delay (stimulus onset asynchrony) of 300ms. Each block of the experiment included 96 targets, except the final block (‘Test’ block), a ‘double block’ which contained 192 targets. The sequence 96 targets in each block followed one of two 12-item sequences; sequence A was 1-2-1-3-4-2-3-1-4-3-2-4 and sequence B was 4-2-4-3-1-2-3-4-1-3-2-1; each sequence (cycle) repeated 8 times within each block (Shanks & Channon 2002). Some individuals may become aware of the sequence and their response time may be reduced as a result. The sequences we used (i.e. SOC sequences, see *Introduction* above) were designed to minimize this as their complexity makes awareness far more unlikely. Two blocks of sequence A were used during the familiarisation phase of the task (A1-A2). Following this, eight blocks of sequence B were presented (B1-B8). After a one-hour break, participants then completed a ‘Test’ block (sequence B).

Insert Fig. 1 about here

Sequence Knowledge Test. Following the Test block, participants completed a Free Generation task (FGT). The FGT is an established task for examining the degree of explicit sequence knowledge and in this study involved the participant making 96 key presses (the same number as in a block) with the aim of generating the sequence they responded to during the training phase of the study. As participants made these freely generated key presses, spatially congruent visual representations of these (i.e., like the target/stimuli in the training phase) appeared on the screen in response to each key press (Perruchet & Amorim 1992; Shanks & Channon 2002). The FGT is considered the optimal way to assess sequence knowledge.

Insert Table 1 about here

Data Analyses

SPSS version 26.0 was used for all statistical analyses. A 2 (group) x 2 (gender) ANOVA was run separately for age, ADC-A subscale total score, ADC checklist total score, BOT-2 Brief Standard Score and percentile; SPM raw score, SPM time and WURST total score. Chi-square run separately for gender and handedness. For the SRT task, a standard approach to analysis was followed. Individual key presses provided accuracy and response time data. Mean accuracy was calculated for each participant and for each block. For RT data, median values for each cycle were calculated and then the mean of these medians was calculated for each block and for each participant. Accuracy and RT data were then subject to a 2 x 9 (Group x Block) ANOVA with repeated measures for *Block*. Familiarisation blocks (i.e., A1 and A2) were not included in the analysis leaving the eight sequence B blocks (i.e., B1-B8) and the Test sequence block For the Free Generation Task, again a typical approach to analysis (Jacoby et al., 1993; Shanks et al., 2005) was followed. Key presses produced a *string* of 96 numbers representing the sequence of key presses by each participant. Consecutive triplets of responses within these strings (i.e., key presses 123, 234, 345 and so on) were examined for congruence with the training sequence. The number of correct triplets achieved by each participant on the Free Generation Task (FGT) was calculated and expressed as a percentage (with 100% being a perfect score). Difference between groups was explored via an independent t-test. The level of significance was set at $p < 0.05$.

Results

Accuracy

Overall mean accuracy was 97% (SD = 3.6%). All participants had a mean accuracy greater than 90% with the exception of one participant in the DCD group (i.e., 82%). This participant was removed from subsequent analyses. Mean accuracy for the two groups and for the different blocks of the task are presented in Fig. 2. Across the nine blocks where the test sequence was presented (i.e., B1 to Test), the groups showed comparable accuracy, F (1, 26) = .02, p = .88. There was a significant main effect of *Block*, F (4.74, 123.12) = 2.61, p = .03; the only pairwise comparison to reach significance was between B1 (mean = 98%) and B5 (mean = 97%), p = .03. There was no interaction, F (4.74, 123.12) = .86, p = .51. To examine whether attention may have influenced the results the same analyses were run using the scores obtained in the WURS-ADHD subscale as covariate. The effect of block was no longer significant, and no interactions were found to be significant. When the same analyses were conducted using the percentile of the BOT-2 Brief as a covariate the effects did not change.

Insert Fig. 2 about here

Initial response time analysis

The ANOVA revealed significant main effects of *Group*, F (1, 26) = 5.77, p = .024, *Block*, F (3.38, 87.89) = 8.69, p < .001 and a *Group* x *Block* interaction, F (3.38, 87.89) = 2.59, p = .05; see Fig. 2 (right panel). The interaction was explained by there being a significant effect of *Block* for the *Control* group, F (3.48, 59.16) = 9.17, p < .001, as RTs became faster across the blocks, but not the *DCD* group, F (2.45, 22.07) = 1.04, p = .28. Importantly, for the *Control* group, in addition to RTs becoming progressively faster between block BI and B8, pairwise comparisons also showed a significant speeding of RTs between block B8 and the Test Block (p < .001). To examine whether attention may have influenced the results the same analyses were run using the scores obtained in the WURS-ADHD subscale as covariate. The results remained the same apart from the effect of block that was no longer significant; no interactions were found to be significant.

Interestingly, when we run the same analyses using the percentile of the BOT-2 Brief as a covariate the above effects and interactions were no longer significant. In our DCD sample only 3 individuals fell within the below average performance (i.e., "probable" DCD) as measured with the BOT-2 Brief whereas the remaining 7 fell within the well-below average performance (i.e., "definite" DCD). When these three individuals were removed from the DCD group the mean RTs across the B and Test blocks were increased suggesting that individuals with "definite" DCD may be slower than those with "probable" DCD. Due to the small numbers, it was not possible to carry out any further statistical analyses for the two DCD subgroups. To explore further whether age had an effect we ran the analyses using age as a covariate. It was only the group effect that remained significant whereas all other interactions were non-significant. Therefore, we can be certain that the group differences did not arise due to age.

Insert Fig. 3 about here

Sequence knowledge

The *Control* group (mean = 51.3%) gained significantly more sequence knowledge than the *DCD* group (mean = 40%), t (22.22) = -2.34, p = .029; see Fig. 3 (left panel).

Subsequent response time analyses. As sequence knowledge may have accounted for the learning demonstrated by the *Control* group, *DCD* group performance was again compared with the *Control* group performance after removing any *Control* group participants whose FGT score fell outside of the range of FGT scores achieved by the *DCD* group (i.e., 34 – 54%). Accordingly, data from seven participants were removed from the *Control* group (see Fig. 3, left panel) and the ANOVA above was repeated. As can be seen in Fig. 4 (right panel), the same pattern of results held for the smaller *Control* group, i.e., there remained a significant effect of *Block*, F (3.61, 36.02) = 10.12, $p < .001$.

Insert Fig. 4 about here

Discussion

This study examined performance on an influential motor sequence learning task (the serial response time task) in adults with and without DCD. Both groups were able to complete the task and showed comparable accuracy; however, response time (RT) performance was markedly different across the two groups. Adults without DCD (control group) showed the typical pattern of data on the task with RTs becoming faster as the task progressed indicative of implicit learning. Adults with DCD (DCD group) showed no such signs of learning. Additionally, the control group acquired reliably greater levels of explicit knowledge of the sequence than the DCD group. Given that the acquisition of such knowledge typically leads to faster RTs, it could have been argued that this explicit knowledge accounted for the differences between the groups. However, further analysis that removed control group participants who acquired greater levels of explicit knowledge continued to show that the control group learned the task implicitly whereas the DCD group did not. This is important as it suggests that participants with DCD may have a deficit in both the implicit learning of a motor skills and in acquiring explicit knowledge about it.

As noted earlier, there is a small number of previous studies that have examined SRT task performance in children with DCD (Blais et al., 2021; Gheysen et al., 2011; Wilson et al., 2003) though until now, not in adults with DCD. Studies have tended to show somewhat inconsistent findings and it is therefore of interest to consider the findings here with these previous studies. Firstly, the finding that our DCD group were generally slower than the control group and also did not demonstrate the typical hallmarks of implicit learning is consistent with the findings in children with DCD by Gheysen et al. (2011). Another study also found generally slower responses in children with DCD but reported no difference in the ability to learn a sequence (Wilson et al., 2005). Our finding that adults with DCD acquired less explicit knowledge regarding the sequence has not been found previously. Indeed, in the only previous study to examine this in some detail, explicit knowledge was found to be comparable across DCD and control groups (Gheysen et al., 2011).

Synthesising data from SRT task-related studies in individuals with DCD is not straightforward. All have differences in the design of the task used and some of used differing approaches to analysis. The findings presented here may contribute to the related uncertainty in some ways, but overall there is now an emerging weight of evidence that points towards individuals with DCD having difficulties in motor sequence learning.

What are the implications of the findings presented here? Firstly, while they should be considered preliminary, the data may point towards an important issue in progressing our understanding in relation to the difficulties with movement that characterise individuals with DCD. This is important both in terms of understanding DCD more deeply and also for optimally design future interventions and offering advice. If individuals with DCD have difficulties in learning motor sequences as shown here, and also fail to acquire explicit knowledge about these sequences in the normal way, it seems likely that learning sequences and patterns of movement in everyday life may also be problematic. Our findings offer clues and suggestions for potential interventions. For example, might working on the development of explicit knowledge about a task prior to physical practice be beneficial? Such development could take different forms such as via visual cues or action observation (Bird et al., 2005). The SRT task has proved a useful model for exploring different approaches to learning in unimpaired individuals (Strangman et al., 2005) as well as in people with other conditions such as stroke (Boyd & Winstein, 2003) and Parkinson's Disease (Wilkinson, et al., 2009).

While studies that test interventions aimed at enhancing motor skill acquisition for individuals with DCD in *real world* situations may be some distance away, building knowledge that can inform such studies is critical if they are ultimately to have any chance of success (Skivington et al., 2021). In the meantime, raising awareness regarding the different difficulties that individual may have when learning a motor skill is informative for those working with affected individuals, with related knowledge influencing the decision-making process where possible.

In summary, the results of this study show that adults with DCD failed to demonstrate the typical signs of implicit (procedural) motor sequence learning on an established and influential sequence learning task. Difficulties in acquiring task-related knowledge may also point towards more complex problems in learning motor skills. The SRT task is well-suited to further investigation in this population and further research is indicated to gain a better understanding of motor sequence learning in adults with DCD.

Limitations and future research

As a preliminary study, there are of course some limitations that should be acknowledged in the present study. While being the first study to investigate motor sequence learning in adults with DCD, our study was small with just eleven participants in the DCD group (though this is larger than some other studies published to date). Given the additional known heterogeneity in the population, whether our sample and results prove to be representative remains to be seen and replication in larger samples would be welcome. There were many strengths in the design of the SRT task used in this study (e.g. sequence design and structure) and our approach of capturing learning by examining the change in RT across blocks of the repeating sequence is an established one (Robertson et al., 2004). Nevertheless, the more typical approach when using the SRT task to measure implicit motor sequence learning is to require participants to complete a block where a novel or random sequence of stimuli is presented following the series of blocks responding to the learned sequence. The typical increase (slowing) of response times when moving from the learned sequence to the novel/random sequence then provides an index of learning. Different approaches have their merits, and where baseline data are not comparable between groups (as in this study), the latter approach may be problematic.

However, in order to maintain greater consistency among studies, we would advise they take the novel/random sequence approach in future. To date, the few studies to examine SRT task performance in participants with DCD have all taken different approaches and this makes comparisons more challenging. We would also advise future studies to pay close attention to sequence structure as was the case in the present study. It may also be possible to enhance the FGT task by adding both an inclusion and exclusion version, as proposed by Destrebecqz and Cleeremans (2001); only the former was used in the present study.

Given the findings presented here, future studies using the SRT task that contrast implicit learning with approaches that provide explicit information about sequences may be revealing; such studies have been informative in individuals with other conditions, for example, stroke (Boyd & Winstein, 2003). Such approaches and larger samples will provide interesting information on which type of learning should be employed by clinicians in the rehabilitation of individuals with DCD and allow the exploration of possible motor sequence learning subtypes within DCD. Lastly, and most importantly the employment of more ecologically (i.e., everyday) valid tasks that investigate the optimal learning of motor skills in individuals with DCD should be a goal for researchers in the field.

Conflict of Interest

The funders have not had any involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication. All authors declare no conflict of interest.

Ethics Statement

The study was approved by the Cross-School Research Ethics Committee of York St. John University (approval number 03072017_Sinani).

Informed Consent Statement

Only participants who gave informed consent were included in this study.

Credit authorship contribution statement

Dr. Charikleia Sinani was involved in conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, visualisation, writing original draft, review and editing. Dr. David Punt was involved in conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, visualisation, writing original draft, review and editing. Ms Rebecca Henderson was involved in data curation, formal analysis, investigation, project administration, visualisation, writing - review and editing. Sang-Dr. Sang-Hoon Yeo conceptualization, data curation, formal analysis, funding acquisition, methodology, resources, software, visualisation, writing - review and editing. Dr. Robert Vaughn was involved in conceptualization, data curation, funding acquisition, methodology, project administration, resources, supervision, visualisation, writing - review and editing.

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Table 1. Group characteristics of the groups including age, MABC-2 checklist, MABC-2 test, SAT scores (means, standard deviations and percentiles) and gender. Statistical comparisons are shown.

	Groups				***Statistics***		
	DCD (N=11)		***Control (N=18)***		***P - value***		
	N / %	***M (SD)***	***N / %***	***M (SD)***	*group*	*gender*	*group x gender*
Age (years)		30.9 (14.7)		25.5 (12.1)	.233[1]	.222[1]	.669[1]
Gender (female/male)	7/4		10/8		.326[2]	-	-
Handedness					.390[2]		
Right	9/81.8		17/94.4				
Left	1/9.1		1/5.6				
Mixed	1/9.1		0/0				
ADC Checklist total		119.4 (16.3)		60.6 (11.3)	.001[1*]	.942[1]	.608[1]
ADC-A (as a child)		31.4 (3.8)		14.6 (5.0)	.001[1*]	.974	.186
ADC-B (currently)		28.8 (5.8)		14.4 (3.3)	.001[1*]	.686	.930
ADC-C (currently)		59.1 (9.0)		31.5 (4.6)	.001[1*]	.885	.856
BOT-2 Brief							
Total Standard Score		37.6 (4.7)		48.4 (8.3)	.001[1*]	.015[1]	.604[1]
Percentile cut-off	<18th		>18th		.001[1*]	.003[1]	.067[1]
Intelligence - RSPM							
Raw Score		11.4 (4.1)		13.5 (3.3)	.120[1]	.277[1]	.300[1]
Response Time (mins)		10.0 (3.3)		9.7 (3.9)	.798[1]	.082[1]	.668[1]
Attention – WURST Total		110.4 (25.0)		56.5 (24.9)	.001[1*]	.5966[1]	.331[1]
WURST ADHD Total		54.8 (9.3)		23.7 (15.2)	.001[1*]	.958	.668

[1] 2 (Group) x 2 (gender) ANOVA, [2]Chi-square, * $P < .001$ considered significant. ADC checklist = Adult Developmental Co-ordination Disorders Checklist (higher scores indicate more problems). BOT-2 Brief = Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, Brief Form (low scores indicate more problems). WURST= Wender Utah Rating Scale (higher scores indicate more problems).

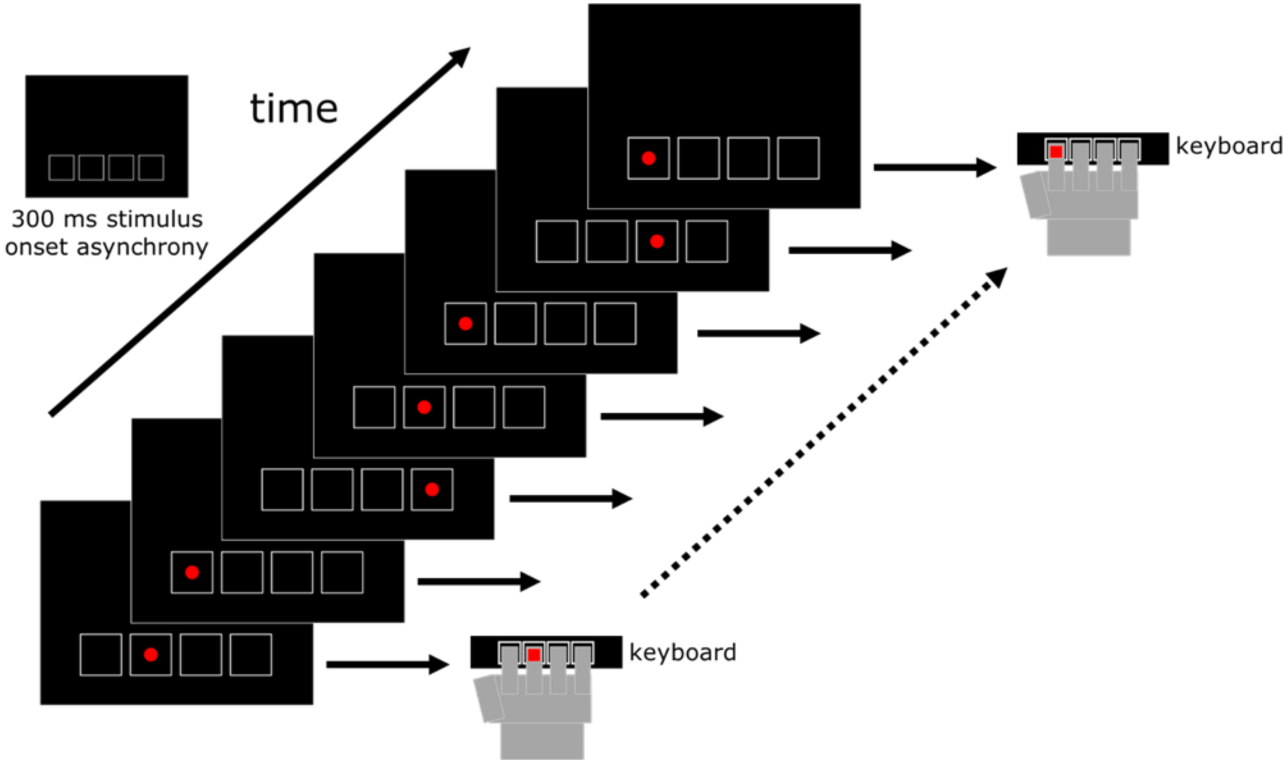


Figure *1*. Schematic representation of the Serial Response Time (SRT) Task; see *Learning Task* for further details.

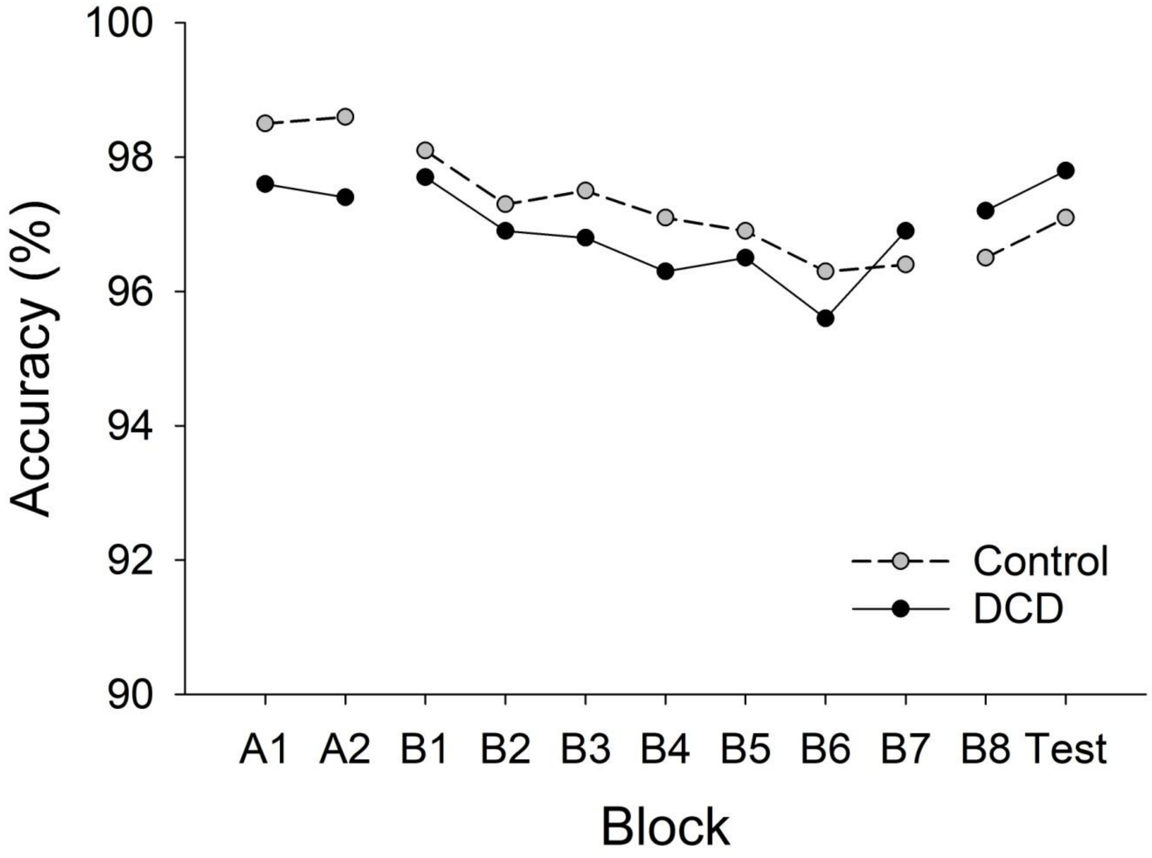
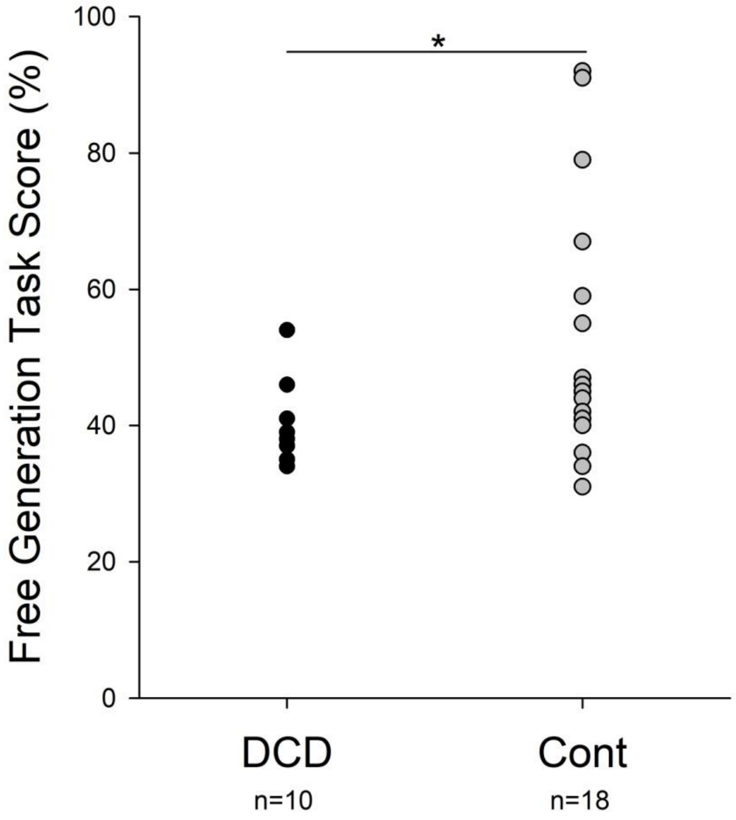


Figure 2. Learning for the serial response time task for the DCD and Control groups: mean accuracy in percentages per sequence (A, B, test) and block for the implicit condition.



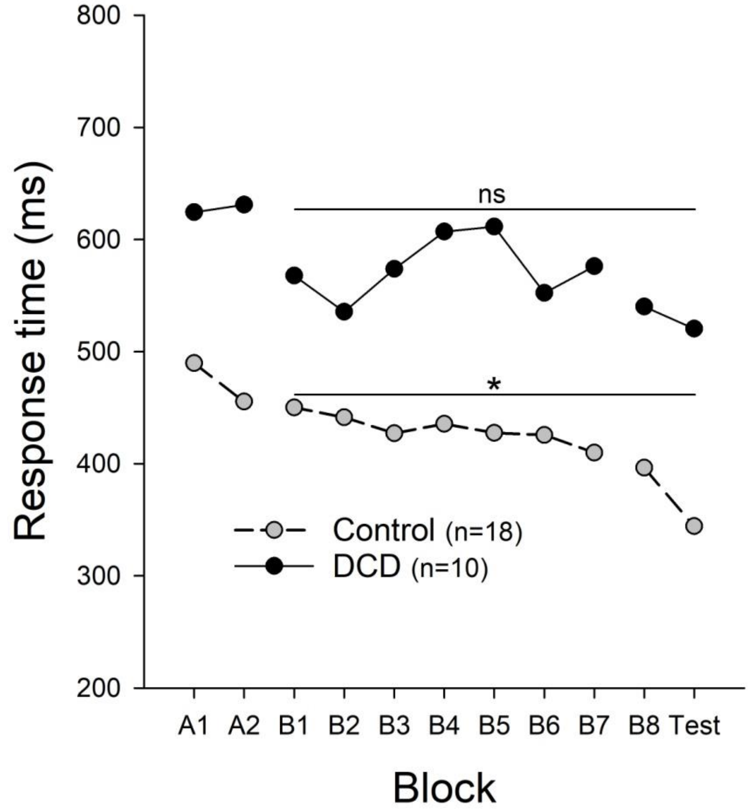


Figure 3. Sequence knowledge as measured using the Free Generation Task for the DCD and Control groups: mean accuracy (left panel). Learning for the serial response time task for the DCD and Control groups: mean response time per sequence (A, B, test) and block for the implicit condition (right panel).

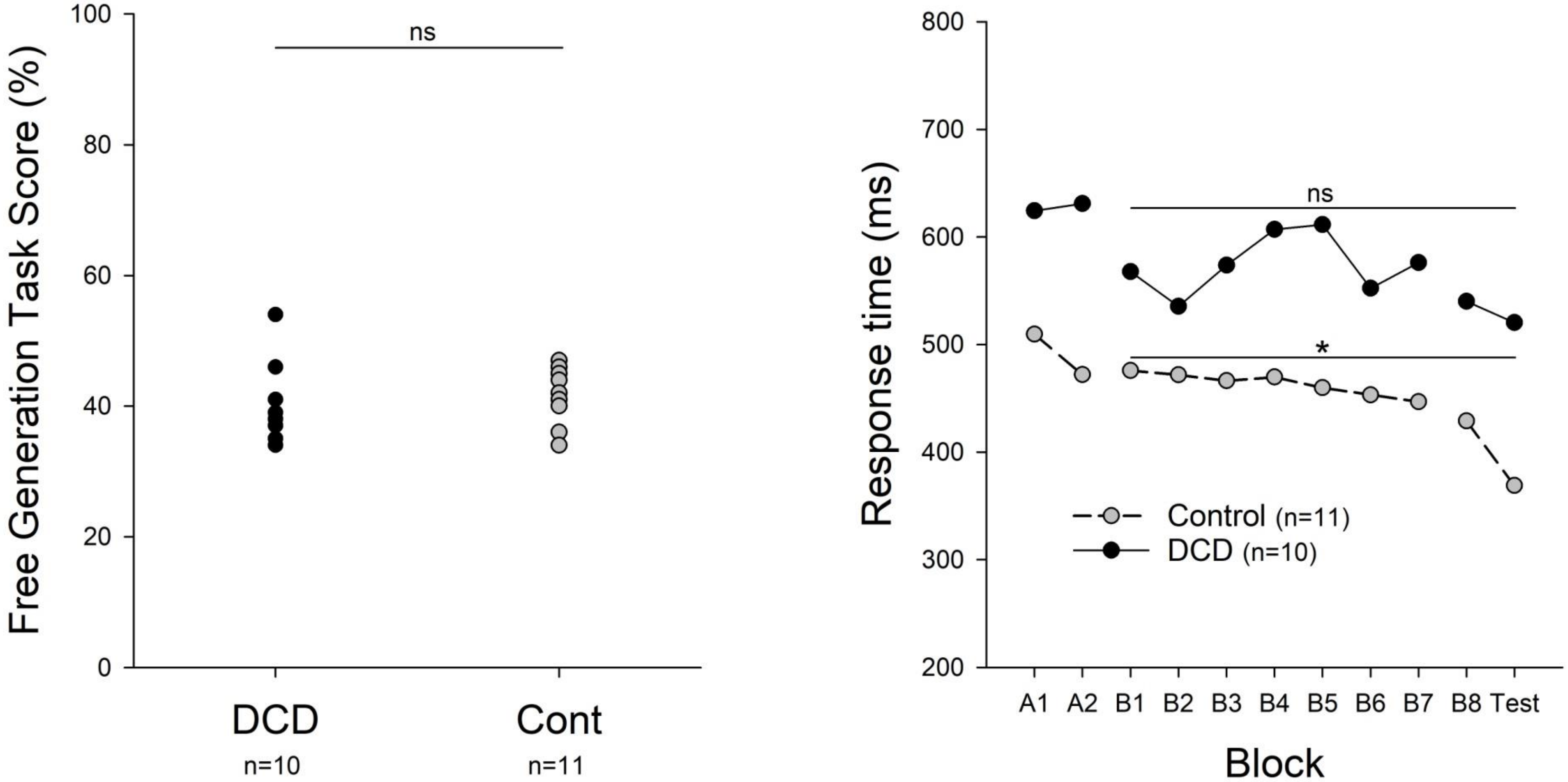


Figure 4. Left panel shows sequence knowledge as measured using the Free Generation Task for participants in the DCD and Control groups (Control group participants whose FGT score fell outside of the range of FGT scores achieved by *DCD* group (i.e., 34 – 54%) were removed). Right panel shows the related learning for the serial response time task by these modified DCD and Control groups.