Running head: INTACT PROCEDURAL MOTOR SEQUENCE LEARNING

Intact Procedural Motor Sequence Learning in Developmental Coordination Disorder

Caroline Lejeune[1,2], Corinne Catale[1,2], Sylvie Willems[2], and Thierry Meulemans[1,2]

Department of Psychology, Behavior and Cognition, Neuropsychology Unit, University of Liège, Belgium

Psychological and Speech Therapy Consultation Center, University of Liège, Belgium

Correspondence concerning this article should be addressed to Caroline Lejeune

Department of Psychology, Behavior and Cognition, University of Liège, B33, Boulevard du Rectorat, 3. 4000 Liège – Belgium.

E-mail: c.lejeune@ulg.ac.be

Abstract

The purpose of the present study was to explore the possibility of a procedural learning deficit among children with Developmental Coordination Disorder (DCD). We tested 34 children aged 6 to 12 years with and without DCD using the serial reaction time task, in which the standard keyboard was replaced by a touch screen in order to minimize the impact of perceptuomotor coordination difficulties that characterize this disorder. The results showed that children with DCD succeed as well as control children at the procedural sequence learning task. These findings challenge the hypothesis that a procedural learning impairment underlies the difficulties of DCD children in acquiring and automatizing daily activities. We suggest that the previously reported impairment of children with DCD on the serial reaction time task is not due to a sequence learning deficit per se, but rather to methodological factors such as the response mode used in these studies.

1. Introduction

Developmental Coordination Disorder (DCD) is a developmental disorder mainly characterized by marked impairments in motor skills, in the absence of neurological or intellectual dysfunction (APA, 2000). Children with the disorder typically have problems acquiring and performing daily activities that require motor coordination, such as handwriting, drawing, eating with cutlery, dressing, tying shoelaces, and sports (throwing a ball, riding a bike, jumping, etc.) (Zwicker, Missiuna, Harris, & Boyd, 2012). These motor difficulties may lead to a high level of dependence on adults and cause the children affective and social discomfort. The mechanisms underlying this disorder, which can have a severe impact on children's daily lives, are still unknown.

One of the hypotheses relevant to DCD that has received some consideration is the idea of a dysfunction in the brain circuits (such as cortico-striatal and cortico-cerebellar circuits) that sustain procedural learning, i.e. the learning and automation of motor skills. This hypothesis has been initially proposed by Nicolson and Fawcett (2007). More specifically, these authors suggested a common impairment procedural learning system in developmental disorders which could explain especially the frequent comorbidity between these disorders. While some studies have reported results which support the presence of a procedural learning deficit in children with dyslexia (Vicari et al., 2005), specific language impairment (Lum, Conti-Ramsden, Page, & Ullman, 2012), and attention deficit hyperactivity disorder (Barnes, Howard, Howard, Kenealy, & Vaidya, 2010), contrasting results have also been obtained, showing for instance that children with specific language impairment are able to learn a new procedural skill as quickly and accurately as children without any developmental disorder (e.g., Gabriel, Maillart, Guillaume, Stefaniak, & Meulemans, 2011).

In DCD, the hypothesis of a procedural learning deficit seems particularly relevant; indeed, several authors have highlighted problems with motor skill acquisition in DCD (e.g., Goodgold-Edwards & Cermak, 1990). Clinically, DCD children have been observed to experience difficulties automatizing their gestures: for instance, in contrast with peers, movements to tie shoes continue to require particular attention, even after a great deal of practice. In support of this procedural learning deficit hypothesis, some studies have showed that dysfunction of cerebellum and basal ganglia might be involved in the pathogenesis of DCD (Brookes, Nicolson, & Fawcett, 2007; Cherng, Liang, Chen, & Chen, 2009; Marien, Wackenier, De Surgeloose, De Deyn, & Verhoeven, 2010; Piek & Dyck, 2004; Zwicker, Missiuna, Harris, & Boyd, 2011). For instance, Zwicker et al. (2011) explored brain activity during motor procedural learning (trail-tracing task using a joystick) in 7 children with DCD and 7 matched controls. DCD children showed significantly less activation than their peers in the cerebellar-parietal and cerebellar-prefrontal circuits. Interestingly, after three days of practice on this trail-tracing task, in children with DCD, contrary to control children, there was no improvement in tracing accuracy. Several behavioral studies have also demonstrated cerebellar dysfunction among children with DCD (Geuze, 2005). For instance, difficulties in motor adaptation learning have been demonstrated in DCD (e.g., Kagerer, Contreras-Vidal, Bo, & Clark, 2006).

Procedural learning is usually defined as a process in which new visuomotor, perceptual, or cognitive skills are acquired through repetitive training (Cohen & Squire, 1980; Willingham, 1998). An experimental paradigm frequently used to explore procedural learning is the serial reaction time paradigm (SRT; Nissen & Bullemer, 1987). In this task, subjects are asked to respond as quickly and accurately as possible to stimuli appearing at different locations on a computer screen by pressing corresponding keys on the keyboard; participants are not told that the stream of stimuli corresponds to a repeating sequence. Learning is demonstrated by improvement in the speed of response across trials and, more specifically, by the difference in response latency between a random block of stimuli and the repeating sequence block, indicating clearly that skill learning was sequence-specific. Neuroimaging studies have demonstrated that procedural sequence learning is supported by the basal ganglia and the cerebellum (e.g., Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994), and the SRT paradigm has been widely used to explore memory abilities in various neurological pathologies characterized by impairments in these regions, such as Parkinson's disease (e.g., Helmuth, Mayr, & Daum, 2000). In children, the SRT task has also been used to explore procedural learning in developmental disorders (e.g., Lum et al., 2012; Vicari et al., 2005)

To our knowledge, only two studies have investigated the motor difficulties of children with DCD with the SRT paradigm. First, Wilson, Maruff, and Lum (2003) explored motor sequence learning with a 10-element long sequence SRT task and noted normal results in 10 children with DCD. Unfortunately, the interpretation of this finding is problematic due to some methodological flaws, such as the absence of structural equivalence between random and repeated sequence blocks. Recently, Gheysen, Van Waelvelde and Fias (2011) used the sequence of Wilson et al. to explore SRT performance in a larger sample of children (18 DCD and 20 control children). These authors matched the random block to the sequence block (i.e., the four locations appeared with the same frequency in the random and sequence blocks) and added another sequence block (administered after the random block) in order to control for the effects of fatigue. In this way, they assured that the increase in reaction times observed for the random block was due to the impossibility of using sequence-specific knowledge with these randomly presented items. Interestingly, in this study, implicit sequence learning seemed to be impaired in children with DCD. However, one question remains unanswered: did these results reflect a deficit in procedural learning as such, or rather a motor deficit? Subjects had to use a response box to press the key corresponding to the target: the possibility remains that the DCD children's impaired performance on the SRT task could have been caused by the perceptuomotor difficulties that characterize DCD. As described by Gabriel, Stefaniak, Maillart, Schmitz, and Meulemans (2012), performance on an SRT task can be affected by deficits in manual dexterity and/or by difficulties matching the location of the target on the screen to the corresponding key. These cognitive and perceptuomotor constraints may affect specific-sequence learning. Indeed, considering the deficits in eye-hand coordination and in sensorimotor and visuospatial processing (Savelsbergh, Whiting, Pijpers, & van Santvoord, 1993; Wilson & McKenzie, 1998), but also in working memory (Alloway, Rajendran, & Archibald, 2009) present in DCD, it might be hypothesized that using a keyboard or a response box is too complex for DCD children.

In this context, the aim of our study was to explore motor sequence learning in children with DCD in an adaptation of the SRT task that reduces (or even eliminates) the cognitive and perceptuomotor constraints associated with the classical SRT task. For this purpose, we used a modified version of the SRT task devised by Gabriel et al. (2012), in which the standard keyboard is replaced by a touch screen. With the touch screen, the motor and cognitive constraints of the task are minimized, because subjects can simply use their dominant hand to touch the target directly on the screen. In addition, a quadrant presentation was employed; with this arrangement the locations can be better separated into large spatial domains (Thomas & Nelson, 2001). On the basis of the procedural deficit hypothesis, we predicted that even with the touch screen as response mode, children with DCD should present difficulties in sequence-specific learning relative to normal controls. Conversely, the observation that the performance levels of children with DCD on the touch screen-based SRT task are similar to those of control children would challenge the procedural deficit hypothesis on the difficulties of DCD children in learning new motor skills.

2. Method

2.1 *Participants*

Thirty-four children aged 6 to 12 years (17 children with DCD and 17 control children matched based on chronological age, gender, mother's education level and verbal IQ score) participated in the study. Descriptive information regarding the two groups is presented in Table 1. All children had a verbal IQ score of more than 85 (based on the Verbal Comprehension Index from WISC-IV, (Wechsler, 2005). The parents were asked to complete an anamnestic questionnaire to ensure that all children were born after a normal gestation period (> 36 weeks), without any obstetric complications, and were free of any psychiatric or neurological disorders. Moreover, control children presented neither motor impairments nor other learning impairments. Informed consent was obtained from the parents of all participating children.

Children from the control group were recruited in mainstream primary schools in the French-speaking part of Belgium.

Children with DCD were recruited from special schools and occupational therapists in the French-speaking part of Belgium. To be included in the study, children had to meet the criteria of the Diagnostic and Statistical Manual of Mental Disorders (2000) for DCD. Motor ability was tested using the French version of the Movement Assessment Battery for Children (M-ABC; Soppelsa & Albaret, 2004). Children with M-ABC total scores below the 15th percentile were classified as having DCD (criterion A). The majority of children (13 out of 17) with DCD scored at or lower than the 5th percentile on the M-ABC. These deficits interfered with academic achievement or activities of daily living, as indicated by a clinically significant score on the M-ABC Checklist (criterion B). This scale was completed by the parents, who were asked to evaluate their children's motor abilities. None had other medical, neurological (criterion C) or intellectual (criterion D) difficulties. Parents also completed the

Conners Parents Rating Scale, a 48-item questionnaire (Dugas, Albert, Halfon, & Nedey-Sayag, 1987) that screens for attention-deficit/hyperactivity disorder (ADHD). None of the children with DCD presented scores above the cutoff score on the hyperactivity and impulsivity scale from Goyette, Conners, and Ulrich (1978). Furthermore, two computerized attention tasks assessing inhibition and flexibility (the Simon inhibition task adapted for children by Catale, Germain, and Meulemans, 2011; the flexibility task from the TAP battery, Zimmermann & Fimm, 1994) and a digit span test (WISC-IV, (Wechsler, 2005) were administrated to all children (results on the executive tasks are presented in Table 1). There was no group difference for reaction times and correct responses on the inhibition and flexibility tasks ($p > .05$). However, children with DCD presented a lower backward digit span than control children (no difference was found in forward digit span).

2.2 Serial Reaction Time (SRT) task

Participants were presented with the modified version of the SRT task developed by Gabriel et al. (2012) where the standard keyboard was replaced with a touch screen in order to reduce the impact of the DCD group’s perceptuomotor coordination difficulties. The touch screen was placed on the laptop screen and was the same size as the monitor (15’’). The laptop screen was open at a 180° angle to the keyboard in order to ensure the most comfortable position possible for the child. The E-Prime software (version 1.1) was used for stimulus presentation and data recording.

In order to keep the children motivated and focused on the task, the test was presented as a game in which a character appears in one of the four windows of a castle (corresponding to the four quadrants, see below). The child’s task was to “liberate” the character as fast as possible by catching it (using his/her dominant hand) with a “magic wand” (pen stylus). The distance between the horizontal and vertical windows was respectively 25 and 14.5 centimetres. The character disappeared once the children had touched the relevant area of the screen with the stylus, or after a maximum time of 4000 ms. The next target appeared after a 250 ms response-stimulus interval.

The experiment included 8 blocks of a four-choice RT task. Participants were given a break after each block. An ambiguous 10-item sequence was employed for this study: 2-4-1-3-4-2-1-4-3-1. Each block consisted of a 10-element-long sequence repeated 8 times (for a total of 80 trials per block). As suggested by Thomas and Nelson (2001), the screen was divided into four large spatial domains, and each stimulus in the sequence was located in a quadrant of the screen (rather than following the linear presentation classically used in SRT tasks). Thus, on each trial, a target appeared at one of the four possible locations (upper left, upper right, lower left, lower right). The sequence was repeated from Block 1 to Block 6, and for the last block (Block 8). This sequence was chosen because each transition between consecutive locations (first-order transition) appears only once within the sequence, and because it did not contain reversals (i.e., ABA), which are known to be especially salient (Reed & Johnson, 1994). In the pseudorandom block (Block 7), the location of the target was randomly determined, except that two consecutive characters could not appear in the same position, and that the four locations appeared with the same frequency as in the repeating sequence in order for the distribution of location frequencies to be the same as in the learning sequence (1 and 4: 30%; and 2 and 3: 20%). In addition, the frequency of first-order transitions (e.g., 2 could be followed by 1 and by 4, and never by 3) was matched between the learning and pseudorandom blocks. Median reaction times (RTs) and accuracy (percentage of correct responses) were computed for each block.

The SRT task was administered in one session. All children were tested individually in a quiet room and seated at approximately 50 cm from the screen. The participants were not informed of the presence of a sequence.

2.3 Explicit awareness test

After the SRT task, children's explicit awareness of the sequence was tested. Subjects were informed that the locations of the characters followed a pattern, and they were administered the free-generation task which consisted in generating a series of trials similar to the sequences they had previously seen (they were asked to avoid repetitions). On this task, each time the child touched the screen, there was a beep informing them that the answer had been recorded. The test stopped after 30 trials. The number of correct triplets was identified as the generation score.

2.4 Statistical methods

An alpha level of .05 was used for all statistical comparisons. Performance during the learning phase was assessed using a repeated measure ANOVA with group (control vs. DCD children) as a between-subjects variable and block as a repeated measure. Greenhouse–Geisser corrections are reported when sphericity was violated.

To measure the degree of awareness of the repeated sequence, an independent t-test was performed first to compare the generation score with chance in the DCD group, and second to compare the generation scores of the two groups. Finally, Spearman's rank correlation tests were conducted to evaluate the relation between explicit knowledge of the sequence and the sequence-specific learning effect.

3. Results

3.1. Serial Reaction Time (SRT)

Accuracy scores during the SRT task were very high in both groups: 97.06 % (SD=2.49) for DCD children and 97.68% (SD=2.43) for control children. The difference between groups was not significant, t(32) = -0.74 p = .47, showing that children with DCD did not make more errors than control children. Because these accuracy scores were very high, they were not analyzed further.

The median reaction time (RT) for each block was presented in Figure 1 for the two groups. First, we performed an ANOVA on RTs with group (control vs. DCD children) as a between-subjects variable, and block (6 levels) as a repeated measure. Results showed a significant effect of block, $F(5, 160) = 13.53$, $p < .001$, $\eta^2p = .30$, confirming the RT improvement from Block 1 to Block 6. Interestingly, there was no effect of group, $F(1, 32) = 2.13$, $p = .15$, $\eta^2p = .06$, and no significant interaction, $F(5, 160) = 0.78$, $p = .57$, $\eta^2p = .02$, indicating that the DCD group responded as quickly as control participants and that RT improvement was similar in the two groups.

Because the improvement between Block 1 and Block 6 could just be due to a general practice effect, in order to show that participants learned sequence-specific information, we compared their performance on the last repeating-sequence block (Block 6) with their performance on the (pseudo) random block (Block 7). An ANOVA with block (Block 6 vs. Block 7) as repeated measure and group (control vs. DCD) as between-subjects variable showed a significant effect of block, $F(1, 32) = 27.00$, $p < .001$, $\eta^2p = .46$, with Block 6 processed faster than Block 7 (pseudorandom block) in both groups. RTs in the two groups were similar, $F(1, 32) = 0.003$, $p = .96$, $\eta^2p < .001$, and the Group × Block interaction was not significant, $F(1, 32) = 1.79$, $p =.19$, $\eta^2p = .05$, showing that sequence learning was globally similar in both groups.

Note that the time difference between Block 6 and Block 7 cannot be interpreted as an effect of fatigue: a comparison between Block 6 and Block 8 did not show any significant block effect, $F(1,32) = 1.34$, $p =.26$, $\eta^2p = .04$, confirming that the RT increase observed in the pseudorandom block was due to sequence-specific learning. Moreover, there was no significant group or interaction effect, $\mathrm{F}(1,32) = 0.93$, $p =.34$, $\eta^2p = .03$, and $\mathrm{F}(1,32) = 0.42$, $p =.52$, $\eta^2p = .01$, respectively.

3.2. Explicit awareness

To measure generation performance, the number of triplets consistent with the sequence was computed for both groups. Given that the generated sequence were 30 trials long, the maximum possible number of correct triplets was 28. The number of correct triplets was computed to obtain the generation score. The chance level was 7.77 (out of 28) [following the methodology of Gheysen et al. (2011), this was computed according to the following logic: with 4 locations, there are 36 possible triplets without repetition of location; with a 10-element sequence, 10 of these triplets are part of the repeated sequence; with 30 trials in the generation task and a maximum of 28 different triplets, the chance level = (28*10)/36 = 7.78]. Children with DCD obtained a mean awareness score of 11.12 (SD = 5.54); control children obtained a mean score of 13.82 (SD = 6.15). A t-test showed that children had some awareness of the repeating sequence (the generation score differed significantly from chance, $p < .05$ for both groups), and a second t-test showed that this awareness was comparable between the two groups, $t(32) = 1.35$, $p = .18$. Note however that the degree of awareness suggested by these scores is very limited: full explicit knowledge of the sequence would have led to a score of 28. Although they differ significantly from chance, scores of 11.12 and 13.82 are actually very low.

Finally, there was no significant correlation between the generation score and the SRT learning index (calculated according to the equation [Block 7 - Block 6] / [Block 6 + Block7], Cherry & Stadler, 1995; Meulemans et al., 1998; Thomas & Nelson, 2001) for either the control or the DCD group ($p > .05$).

4. Discussion

Despite the fact that children with DCD experience difficulties learning motor skills in everyday life, to date, and quite surprisingly, motor procedural learning in developmental coordination disorder has received very little attention. Such research on skill learning in

DCD is needed to identify the precise cognitive mechanisms underlying the main difficulty in this disorder.

The purpose of the present study was thus to explore the possibility of a procedural learning deficit among children with DCD. This hypothesis has been suggested by several authors (Gheysen et al., 2011; Nicolson & Fawcett, 2007) and seemed to receive support from some studies which have shown that a dysfunction of brain structures (such as the cerebellum and basal ganglia) which are heavily involved in the acquisition of motor skills might be involved in the pathogenesis of DCD. More specifically, we compared the performance of children with and without DCD on a variant of the Serial Reaction Time task (Gabriel et al., 2012) that reduces the potential impact of perceptuomotor coordination difficulties on the SRT performance of children with DCD. The logic for this choice was that the deficits displayed by DCD children in the SRT task might be caused by motor and cognitive deficits associated with this disorder, and not by an inability to learn sequential information per se.

Our results showed that children with DCD responded as quickly as their peers in all blocks and that reaction time improvement from Block 1 to Block 6 was similar in the two groups. Likewise, accuracy scores on the SRT task were high and did not differ between groups. Contrary to procedural learning deficit hypothesis, DCD children’s success at acquiring sequence-specific knowledge did not differ from that of control children (as attested by the difference in performance between Blocks 6 and the pseudorandom block which reflects our participants’ ability to learn information specifically related to the sequence with which they were confronted). After the learning phase, a generation task (which measures the degree of awareness of the repeated sequence) indicated that the children’s degree of awareness of the sequence was low but significant, and that it was similar between DCD and control groups. However, no relation was found between explicit knowledge of the sequence and the procedural learning index. Thus, although children had some awareness of the repeated sequence at the end of the learning phase, they did not use this knowledge to increase their performance on the SRT task. Apart from the fact that these results confirm that the degree of explicit knowledge was similar in the two groups, they also suggest that control children and children with DCD did not differ with respect to the learning strategies that they used on the SRT task; more specifically, they did not differ in their use of conscious strategies to perform the task.

Our finding, showing that children with DCD present the same degree of specific sequence learning as control children, challenges the procedural learning deficit hypothesis. Wilson et al. (2003) had already reached the same conclusion, but due to methodological flaws their results were subject to question (lack of structural equivalence between random and repeated sequence blocks). Recently, Gheysen et al. (2011) used the sequence of Wilson et al., while improving the methodology, and showed contrasting results: children with DCD failed to learn the visuo-motor sequence. In contrast with this study, we observed specific learning of sequential regularities, with our DCD children (as well as control children) presenting a significant RT increase between the sixth learning block and the pseudorandom block (Block 7). Moreover, a comparison between the sixth block and the last block did not show any significant difference, which shows that the difference between Block 6 and Block 7 cannot be interpreted as an effect of fatigue. We suggest that the differences between the two studies are not related to an implicit sequence learning deficit in children with DCD per se, but rather to confounding variables resulting from methodological factors, notably the response mode required by the standard SRT paradigm. While in the standard SRT task the response involves using the index and middle fingers of both hands to press the key on a keyboard or a response box, in our study the motor response involves movements of the whole arm: participants had to touch the location on the screen where the target appeared. Thus, in the standard SRT task, children can be disadvantaged by the motor demands of the task. Furthermore, they have to keep the correspondence between the position of the target on the screen and the corresponding key on the response box in working memory. The tests used to confirm the diagnosis revealed that the children with DCD presented difficulties in motor abilities but also in working memory in comparison to their peers. These deficits could affect their performance during the SRT task. The interest of the touch screen is that it requires less fine precision and visual-motor coordination (Gabriel et al., 2012). With this adaptation of the SRT task, and in contrast to Gheysen et al., our results show similar speed and accuracy in the two groups, confirming that the response mode involving the touch screen is appropriate for children with motor deficits such as those presented by children with DCD. Moreover, in the standard SRT task, both hands (dominant and non-dominant) are used, whereas responses are made only with the dominant hand in this modified version of the SRT task. Previous research has shown that DCD children perform poorly with the nonpreferred hand on a pointing task involving hemispheric transfer of information (Sigmundsson, Ingvaldsen, & Whiting, 1997; Sigmundsson & Whiting, 2002). These authors hypothesized that this could be due to a problem in the maturation of the corpus callosum in DCD. This deficit could thus impair performance on bimanual versions of the SRT task such as the one used by Gheysen et al. Previous studies have shown the key role of the corpus callosum in SRT tasks requiring a bimanual response (e.g., De Guise & Lassonde, 2001). De Guise and Lassonde showed that young children who presented callosal immaturity had difficulties learning the visuomotor sequence in the bimanual condition, but no difficulty in the unimanual condition. It would be interesting to further investigate this point by replicating this study in children with DCD.

Interestingly, Gheysen et al. (2011) administered a generation task to test whether the children had been able to develop explicit knowledge; they found that DCD and control children acquired some explicit knowledge of the repeating sequence and that the amount of such awareness was comparable in the two groups. On this basis, they suggested that the core of the problem in DCD during the SRT task could be a motor planning deficit rather than an inability to detect and learn the statistical regularities in sequential material. Our results are consistent with this view. In this context, performance during procedural sequence learning in DCD children appears to be sensitive to the motor demands of the task, and would be particularly affected when the response mode requires too much precision and motor coordination.

It is important to note that the difference between the results presented here and those of previous studies cannot be due to the characteristics of the sequence used, and specifically its statistical structure. Indeed, the sequence used by Gheysen et al. (2011; as well as by Wilson et al., 2003) comprised the triplet “141”, a reversal, known to be a particularly salient combination of transitions (Reed & Johnson, 1994). In addition, in these studies the sequence could be learned by detecting some first-order transitions (for instance, the transition 1-3 appears once in the sequence, while the transition 1-4 appears twice and 1-2 never appears; participants could thus learn that 4 was the most likely response to follow 1), a problem that the authors tried to control in the random block (in which the four locations appeared with the same frequency as in the sequence blocks). However, they did not control the frequency of the first-order transitions in the random sequence. In our experiment, we chose a 10-item fixed ambiguous sequence (2-4-1-3-4-2-1-4-3-1) in which no first-order transition is repeated. In our pseudorandom block (Block 7), the four locations appeared with the same frequency as in the repeating sequence, and the frequency of first-order transitions (e.g., 2 is followed by 1 but never by 3) was matched between the learning and pseudorandom sequences. With these methodological precautions, differences between the learning and pseudorandom blocks cannot be explained by the frequency of the locations or first-order transitions (Karatekin, Marcus, & White, 2007). Therefore, the results we obtained with our DCD children reflect the learning of at least second-order associations (i.e., more than pairwise information).

Another methodological difference concerns the learning phase, which was longer in our study (more than 80 trials in comparison with the study of Gheysen et al., 2011), hence giving the participants more opportunity to learn the sequence.

Finally, although the response mode (touch screen vs. response box) may have been the most influential determinant of our subjects' performance, other elements such as diagnostic criteria could also explain the discrepancy between the results presented here and those of previous studies. Gheysen et al. (2011) included children with scores below the 5th percentile in the M-ABC, whereas the 15th percentile was used in our study. It thus might have been that our children with DCD presented less severe motor deficits. However, this explanation can be rejected because only four of the children in our sample scored above the 5th percentile on the M-ABC (P 14.2, P 9.7, P 6,2, and P 5.1). Results regarding sequence learning remain the same when these four children are excluded from analyses. Furthermore, complementary analyses did not reveal any significant correlation between procedural learning index and the severity of motor difficulties (scores on the M-ABC).

5. Conclusion

To conclude, the results we obtained on sequence learning with the SRT task, which is known to be particularly sensitive to cerebellum and basal ganglia dysfunction (Doyon et al., 1997; Mayor-Dubois, Maeder, Zesiger, & Roulet-Perez, 2010), suggest that procedural motor sequence learning is preserved in DCD. The important result of the present study is that motor specific-sequence learning can be observed in DCD children providing that the response mode does not create difficulties due to the cognitive and motor deficits that characterize this disorder. Although this study contributes to better understanding the extent of the motor deficits in DCD, it is important to highlight that our results cannot be generalized to other procedural skills, whose preservation in DCD children will have to be determined by future research. Indeed, procedural learning cannot be regarded as a homogeneous system;

depending on the task and the type of learning (incidental versus intentional), the cognitive mechanisms and the cerebral areas involved can be different. Studies on procedural learning in DCD are still too limited, and research in this area should continue in the future in order to further our understanding of the exact nature of the motor learning difficulties involved in DCD but also in order to guide the cognitive remediation. Notably, it would be interesting to explore these children’s ability to learn more complex sequences (for example, containing probabilistic transitions) or other forms of procedural skills, such as mirror tracing (involving the adaption of movements to environmental changes), which is known to be particularly sensitive to cerebellar damage (Doyon, Penhune, & Ungerleider, 2003).

References

Alloway, T. P., Rajendran, G., & Archibald, L.M.D. (2009). Working Memory in Children With Developmental Disorders. *Journal of Learning Disabilities, 42*(4), 372-382.

Association American Psychiatric. (2000). *Diagnostic and Statistical Manual of Mental Disorders. Text Revision* (4th ed.). Washington: American Psychiatric Association.

Barnes, K. A., Howard, J.H., Howard, D.V., Kenealy, L., & Vaidya, C. J. (2010). Two Forms of Implicit Learning in Childhood ADHD. *Developmental neuropsychology, 35*(5), 494-505.

Brookes, R.L., Nicolson, R.I., & Fawcett, A.J. (2007). Prisms throw light on developmental disorders. *Neuropsychologia, 45,* 1921-1930.

Catale, C., Germain, S., & Meulemans, T. (2011). Exploration of perceptive and motor inhibition in children with traumatic brain injury. *Perceptual and Motor Skills, 112,* 667-679.

Cherng, R. J., Liang, L. Y., Chen, Y. J., & Chen, J. Y. (2009). The effects of a motor and a cognitive concurrent task on walking in children with developmental coordination disorder. *Gait and Posture, 29*(2), 204-207.

Cherry, K. E., & Stadler, M. A. (1995). Implicit learning of a nonverbal sequence in younger and older adults. *Psychology and aging, 10*(3), 379-394.

Cohen, N. J., & Squire, L. R. (1980). Preserved learning and retention of pattern-analyzing skill in amnesia: dissociation of knowing how and knowing that. *Science, 210*(4466), 207-210.

De Guise, E., & Lassonde, M. (2001). Callosal contribution to procedural learning in children. *Developmental Neuropsychology, 19*(3), 253-272.

Doyon, J., Gaudreau, D., Laforce, R., Jr., Castonguay, M., Bedard, P. J., Bedard, F., & Bouchard, J. P. (1997). Role of the striatum, cerebellum, and frontal lobes in the learning of a visuomotor sequence. *Brain and Cognition, 34*(2), 218-245.

Doyon, J., Penhune, V., & Ungerleider, L.G. (2003). Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning. *Neuropsychologia, 41*(3), 252-262.

Dugas, M., Albert, E., Halfon, O., & Nedey-Sayag, M.C. *(*1987). *L'hyperactivité chez l'enfant*. Paris: Presses Universitaires de France, Collection nodules.

Gabriel, A., Maillart, C., Guillaume, M., Stefaniak, N., & Meulemans, T. (2011). Exploration of serial structure procedural learning in children with language impairment. *Journal of the International Neuropsychological Society, 17*(2), 336-343.

Gabriel, A., Stefaniak, N., Maillart, C., Schmitz, X., & Meulemans, T. (2012). Procedural visual learning in children with specific language impairment. *American Journal of Speech-Language Pathology, 21*, 329-341.

Geuze, R. H. (2005). *Le trouble de l'acquisition de la coordination: évaluation et rééducation de la maladresse chez l'enfant*. Marseille: SOLAL.

Gheysen, F., Van Waelvelde, H.D., & Fias, W. (2011). Impaired visuo-motor sequence learning in Developmental Coordination Disorder. *Research in Developmental Disabilities, 32*, 749-756.

Goodgold-Edwards, S., & Cermak, S. (1990). Integrating motor control and motor learning concepts with neuropsychological perspectives on apraxia and developmental dyspraxia. *American Journal of Occupational Therapy, 44*, 431-439.

Goyette, C. H., Conners, C. K., & Ulrich, R. F. (1978). Normative data on revised Conners Parent and Teacher Rating Scales. *Journal of Abnormal Child Psychology, 6*(2), 221-236.

Helmuth, L. L., Mayr, U., & Daum, I. (2000). Sequence learning in Parkinson's disease: a comparison of spatial-attention and number-response sequences. *Neuropsychologia, 38*(11), 1443-1451.

Jenkins, I. H., Brooks, D. J., Nixon, P. D., Frackowiak, R. S., & Passingham, R. E. (1994). Motor sequence learning: a study with positron emission tomography. *Journal of neuroscience the official journal of the Society for Neuroscience, The, 14*(6), 3775-3790.

Kagerer, F. A., Contreras-Vidal, J. L., Bo, J., & Clark, J. E. (2006). Abrupt, but not gradual visuomotor distortion facilitates adaptation in children with developmental coordination disorder. *Human Movement Science, 25*(4-5), 622-633.

Karatekin, C., Marcus, D. J., & White, T. (2007). Oculomotor and manual indexes of incidental and intentional spatial sequence learning during middle childhood and adolescence. *Journal of Experimental Child Psychology, 96*(2), 107-130.

Lum, J. A., Conti-Ramsden, G., Page, D., & Ullman, M. T. (2012). Working, declarative and procedural memory in specific language impairment. *Cortex, 48*(9), 1138-1154.

Marien, P., Wackenier, P., De Surgeloose, D., De Deyn, P. P., & Verhoeven, J. (2010). Developmental coordination disorder: disruption of the cerebello-cerebral network evidenced by SPECT. *Cerebellum, 9*(3), 405-410.

Mayor-Dubois, C., Maeder, P., Zesiger, P., & Roulet-Perez, E. (2010). Visuo-motor and cognitive procedural learning in children with basal ganglia pathology. *Neuropsychologia, 48*(7), 2009-2017.

Meulemans, T., Van der Linden, M., & Perruchet, P. (1998). Implicit sequence learning in children. *Journal of Experimental Child Psychology, 69*(3), 199-221.

Nicolson, R. I., & Fawcett, A. J. (2007). Procedural learning difficulties: reuniting the developmental disorders? *Trends in Neurosciences, 30*(4), 135-141.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19*, 1-32.

Piek, J. P., & Dyck, M. J. (2004). Sensory-motor deficits in children with developmental coordination disorder, attention deficit hyperactivity disorder and autistic disorder. *Human movement science, 23*(3-4), 475-488.

Reed, J., & Johnson, P. (1994). Assessing implicit learning with indirect tests: Determining what is learned about sequence structure. *Journal of experimental psychology Learning, memory, and cognition, 20*, 585-594.

Savelsbergh, G. J., Whiting, H. T., Pijpers, J. R., & van Santvoord, A. A. (1993). The visual guidance of catching. *Experimental Brain Research, 93*(1), 148-156.

Sigmundsson, H., Ingvaldsen, R. P., & Whiting, H. T. (1997). Inter- and intrasensory modality matching in children with hand-eye coordination problems: exploring the developmental lag hypothesis. *Developmental Medicine and Child Neurology, 39*(12), 790-796.

Sigmundsson, H., & Whiting, H. T. (2002). Hand preference in children with developmental coordination disorders: cause and effect? *Brain and Cognition, 49*(1), 45-53.

Soppelsa, R., & Albaret, J. M. (2004). *Batterie d'Evaluation du Mouvement chez l'Enfant - M-ABC*. Paris: Editions du Centre de Psychologie Appliquée.

Thomas, K. M., & Nelson, C. A. (2001). Serial reaction time learning in preschool- and school-age children. *Journal of Experimental Child Psychology, 79*(4), 364-387.

Vicari, S., Finzi, A., Menghini, D., Marotta, L., Baldi, S., & Petrosini, L. (2005). Do children with developmental dyslexia have an implicit learning deficit? *Journal Neurology of Neurosurgy and Psychiatry, 76*, 1392-1397.

Wechsler, D. (2005). *Wechsler intelligence scale for children – Fourth edition*. Paris: Les Editions du Centre de Psychologie Appliquée.

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105*(3), 558-584.

Wilson, P. H., Maruff, P., & Lum, J. (2003). Procedural learning in children with developmental coordination disorder. *Human Movement Science, 22*(4-5), 515-526.

Wilson, P. H., & McKenzie, B. E. (1998). Information processing deficits associated with developmental coordination disorder: a meta-analysis of research findings. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 39*(6), 829-840.

Zimmermann, P., & Fimm, B. (1994). *Tests d'évaluation de l'attention (TEA*) – Version 1.02, manuel d'utilisation. Würselen, Germany: Psytest.

Zwicker, J. G., Missiuna, C., Harris, S. R., & Boyd, L. A. (2011). Brain activation associated with motor skill practice in children with developmental coordination disorder: an fMRI study. *International Journal of Developmental Neuroscience, 29*(2), 145-152.

Zwicker, J. G., Missiuna, C., Harris, S. R., & Boyd, L. A. (2012). Developmental coordination disorder: A review and update. *Eur J Paediatr Neurol, 16*(6), 573-581.

Table 1

Basic demographic data, verbal IQ scores, and executive performance in both groups

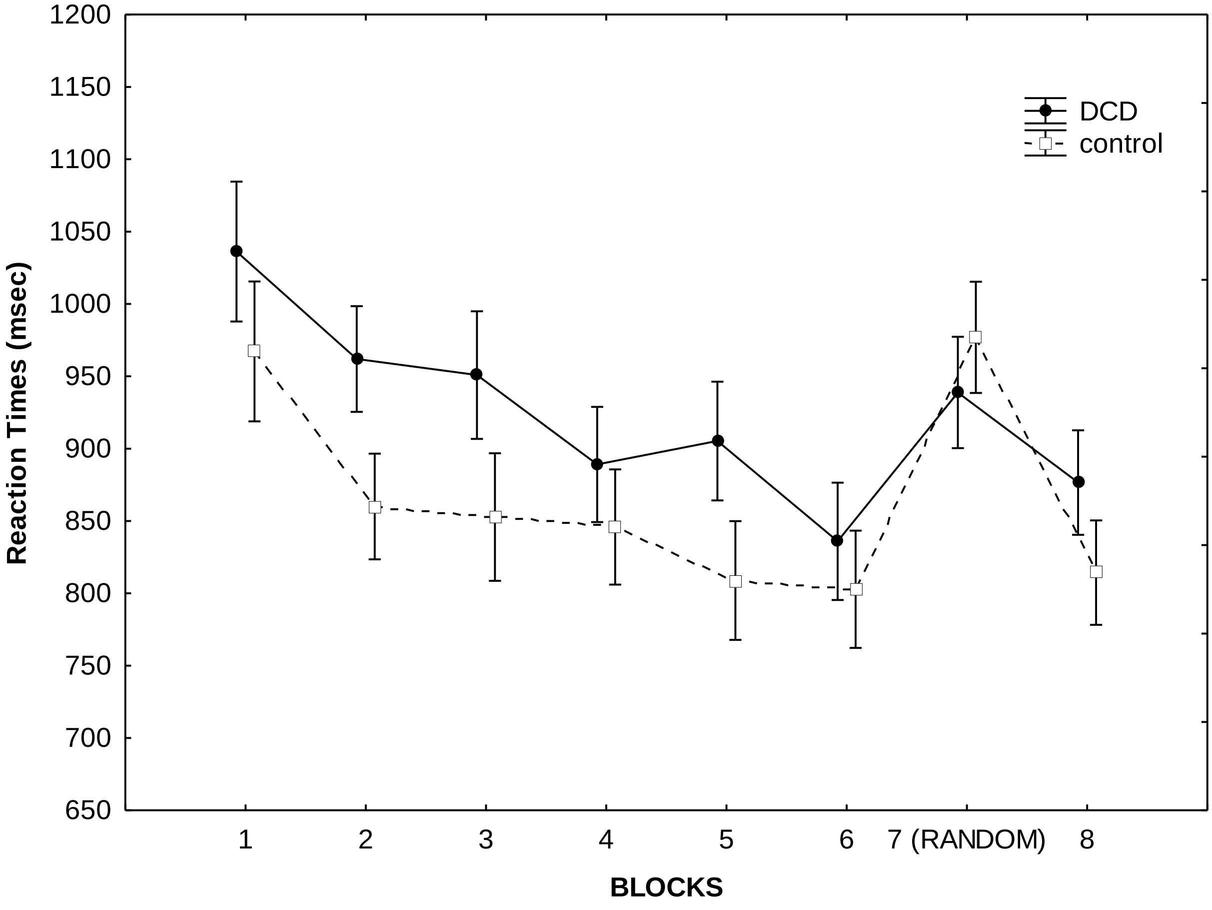
	DCD (n = 17)		Control (n = 17)		*t*(32)	*p*
	M	SD	M	SD		
Gender (male/female)	11/6		11/6			
Age (years)	9.12	1.66	9.08	1.62	.07	.94
Mother's education level[a]					2.93	.40
VCI (WISC-IV)	111.94	10.36	109.29	12.49	.90	.37
Inhibition task (reaction times)	875.97	203.93	799.68	135.14	1.29	.21
Inhibition task (correct responses)	88.68	9.48	92.35	7.58	-1.25	.22
Flexibility task (reaction times)	1268.38	287.23	1187.00	236.72	.90	.37
Flexibility task (correct responses)	88.35	7.01	91.88	5.41	-1.64	.11
Fordward digit span	4.94	0.90	5.29	0.69	-1.29	.21
Backward digit span	3.23	0.66	3.82	0.64	-2.64	.01

Note. DCD, children with developmental coordination disorder; M, mean; SD, standard deviation; VCI, Verbal Comprehension Index; WISC-IV, Wechsler Intelligence Scale for Children

[a] Mother's education level: Education level was rated for each child from 1 to 5: levels ranged from "primary education" to "higher education"; χ^2 test was used for analysis

Figure Caption

Figure 1. Learning patterns for children with DCD (circle) and control children (square). Data points indicate the mean of median reaction times for each block. Error bars represent standard errors.


Reaction Times (msec)
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
1
2
3
4
5
6
7 (RANDOM)
8
BLOCKS
DCD
control