Procedural learning and automatization process in children with developmental coordination disorder and/or developmental dyslexia

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Abstract

Objective: There is increasing evidence to suggest that developmental dyslexia (DD) and developmental coordination disorder (DCD) actually form part of a broader disorder. Their frequent association could be justified by a deficit of the procedural memory system, that subtends many of the cognitive, motor and linguistic abilities that are impaired in both DD and DCD. However, studies of procedural learning in these two disorders have yielded divergent results, and in any case no studies have so far addressed the issue of automatization (dual-task paradigm).

Methods: We administered a finger tapping task to participants aged 8–12 years (19 DCD, 18 DD, and 22 with both DD and DCD) to explore procedural learning and automatic movements in these three groups of children, comparing motor performances at the prelearning stage, after 2 weeks of training, and in a post-training dual-task condition.

Results: First, results indicated that all the children were able to learn a sequence of movements and even automatize their movements. Second, they revealed between-groups differences in procedural/automatization learning abilities, setting the DCD group apart from the other two. Third, contrary to our expectations concerning comorbidity, they suggested that the DD + DCD association does not have an additional impact on behavioral performances.

Keywords:
Procedural memory
Automaticity
Dual-task
Comorbidity
Learning disorder

1. Introduction

Neurodevelopmental disorders such as developmental dyslexia (DD), developmental coordination disorder (DCD), specific language impairment (SLI), and attention deficit hyperactivity disorder (ADHD) frequently co-occur, even if precise percentages may vary (Kaplan, Crawford, Cantell, Kooistra, & Dewey, 2006). Some of these comorbid associations have attracted considerable attention, as they raise the question of shared aetiological bases. These include the DD and SLI association, as regards the phonological deficit hypothesis (Catts, Adlof, Hogan, & Weismer, 2005; Ramus, Marshall, Rosen, & van der Lely, 2006).

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1.1. DD, DCD and the overlap between the two

DD is a persistent disorder that affects a sizeable proportion (5–10%) of the school-age population (Peterson & Pennington, 2012). Children with DD (or specific reading disability) have reading deficits despite adequate intelligence, normal sensory abilities, conventional instruction, sociocultural opportunity and school education (World Health Organization, 1993). DD is widely acknowledged to be a language-based disorder characterized by difficulties in phonological processing (Ramus & Szenkovits, 2008). Substantial evidence has also established the neurobiological origin of DD (Peterson & Pennington, 2012).

DCD, or specific developmental disorder of motor function, is a persistent disorder affecting 2–7% of school-age children (Lingam, Hunt, Golding, Jongmans, & Emond, 2009) in whom the acquisition and execution of coordinated motor skills is below that expected for a given age and opportunity for skill learning, in the absence of intellectual disability (APA, 2013; Blank, Smits-Engelsman, Polatajko, & Wilson, 2012). Children with DCD have both gross and fine motor skill difficulties that include difficulty with postural control, motor learning and sensorimotor coordination. These interfere considerably with activities of daily life (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013).

The aetiology of DD and DCD has yet to be elucidated, probably because both disorders have multifactorial origins. That said, motor impairments in DD were observed long ago (Denckla, 1985; Haslum, 1989), and there is a substantial overlap between the two disorders, with over half of all children with DD having DCD and vice versa (Chaix et al., 2007; Haslum & Miles, 2007). This, of course, raises the question of shared aetiological bases.

1.2. Cerebellum/procedural deficit hypothesis

Supported by the fact that the cerebellum is centrally involved in language, reading-related activities and motor skills, the cerebellum deficit hypothesis (Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 2001) provides a plausible explanation for the co-occurrence of DD and DCD, or in any case of DD and motor impairments. This theoretical framework, initially centered around DD, has been continually revised, expanded and improved over the past 20 years, recently gravitating toward a neural system typology for learning difficulties (Nicolson & Fawcett, 2007, 2011). In this typology, the authors contrast general learning disabilities secondary to an impairment of the declarative learning system (i.e., intellectual developmental disorder) and developmental disorders secondary to an impairment of the procedural learning system (i.e., ADHD, SLI, DD, DCD). Their hypothesis is based on the fact that some children with learning disorders have particular difficulty acquiring skills related to procedural learning or automaticity, including impairments of motor or language functions, working memory, executive functions (attention, planning), visuospatial regulation, oculomotor and visuoperceptual functions. For the authors, this tangle of different procedural learning impairments in specific developmental disorders is crucial for understanding learning disabilities. Brain imaging studies have shown that the automaticity and procedural learning system depends largely on corticostriatal and/or corticocerebellar circuits (Doyon et al., 2009). Authors therefore suggest that impairments in these circuits explain deficits mainly associated with learning disorders, procedural impairment in these disorders and the overlap between them. According to this view, children with learning disorders fail to automate new cognitive and/or motor procedures. In the special case of DD and/or DCD, procedural impairment may therefore explain difficulties in both language and motor skills – a view supported by experimental data and neuroimaging studies revealing cerebellar and/or striatal abnormalities in both disorders (Bo & Lee, 2013; Brookes, Nicolson, & Fawcett, 2007; Stoodley & Stein, 2011, 2013).

1.3. Acquisition of procedural motor skills

Procedural learning is usually defined as a process in which new skills (motor, perceptual, or cognitive) are acquired through repetitive training. This acquisition, especially of a new motor skill, can be divided into three distinct stages originally described by Fitts (1964), and since renamed and modeled by Doyon et al. (2009). In the first, early fast learning stage, in which the individual is first exposed to a task that involves training and repeated engagement with the procedure being learned (Rattoni, Escobar, Pawlik, & Rosenzweig, 2000), performance greatly and rapidly improves in the course of a single training session, with an improvement being observed within a matter of minutes or even seconds (online learning). This improvement follows a power function curve, and performance gradually reaches asymptote, reflecting saturated learning (Hauptmann, Reinhart, Brandt, & Karni, 2005). In the second, slow learning phase (consolidation), incremental gains in performance can be observed over several sessions of practice, and may be seen within days if not hours, sometimes even without further practice (phenomenon referred to as offline learning; Hauptmann et al., 2005). These memory traces become increasingly robust and resistant to disruption (Walker, 2005). Following successful completion of the acquisition and consolidation stages, a third, autonomous stage (automatization) is believed to occur without intent or awareness (Stickgold & Walker, 2005). This automatic stage allows for the transition from controlled to more efficient performance: the skill becomes fluent and even more resistant to interference, allowing it to be performed in a range of contexts with limited demands on attentional resources (Seger & Spiering, 2011; Stefanidis, Scerbo, Korndorffer, & Scott, 2007). Automaticity, which probably relies on sleep (Walker, Stickgold, Alsop, Gaal, & Schlag, 2005), refers in this context to a shift in the brain
networks supporting performance, such that the task can be performed (i) effortlessly even when attention is directed elsewhere (as in dual-task situations; Seger & Spiering, 2011), and (ii) without paying attention to the movements being produced (Poldrack et al., 2005).

In the particular case of motor sequence learning tasks, the paradigm used to study the procedural learning and automatization of skills involves testing participants under both single-task and dual-task conditions (Doyon et al., 2009). Participants perform the procedural motor task before and after many days of behavioral training. The motor task is also performed concurrently with a secondary cognitive task (e.g., tone counting, picture naming, etc.) after training. The diminishing cost of dual-task performance (interference with and attendant decrease in performance on primary task when participants are placed in a dual-task condition) can then be used as an index of automaticity.

1.4. Procedural motor learning in DD and DCD

Deficits in procedural motor skills play a prominent role in theories of both DD and DCD. In the light of the cerebellum/procedural deficit hypothesis, motor sequence tasks have been extensively used to examine procedural motor learning in DD (for a review, see Folia et al., 2008; Lum, Ullman, & Conti-Ramsden, 2013). The automatization deficit in DCD has also been explored with the traditional motor sequence paradigm, albeit less frequently (Bo & Lee, 2013). In both cases, however, studies have yielded inconsistent results. Some of them have revealed impairment in sequence learning among children with DCD (Gheyesen, Van Waeyelde, & Fias, 2011) or DD (Howard, Howard, Japikse, & Eden, 2006; Jimenez-Fernandez, Vaquero, Jimenez, & Defior, 2011; Menghini, Hagberg, Caltagironi, Petrosini, & Vicari, 2006; Vicari et al., 2005; or see Lum et al., 2013, for a meta-analysis). Others, however, have reported intact sequence learning after proper training in individuals with DCD (Lejeune, Catale, Willems, & Meulemans, 2013; Wilson, Maruff, & Lum, 2003) or DD (Gabay, Schiff, & Vakil, 2012a, 2012b; Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006; Waber et al., 2003). Discrepancies between studies are probably due to differences in sampling, procedures, or experimental design. However, even though several studies have demonstrated that individuals with DD and DCD can successfully perform simple or sequential finger movements after practice, two major limitations need to be addressed. First, as pointed out by Orban, Lungu, and Doyon (2008), the majority of these studies focused solely on learning in the fast acquisition stage, disregarding the later stages that are believed to be involved in the process of skill learning. Second, the question of whether or not the participants achieved automaticity remains unanswered, as a dual-task (interference) paradigm was not applied. Although several studies have tested the influence of a concurrent cognitive task on motor task performance in children with DD or DCD, their enquiry was confined to postural control and balance probably owing to cerebellar–vestibular impairment in the DD population and difficulties with balance in children with DCD. Nevertheless, even though they fall slightly beyond the ambit of the present study, it is worth mentioning that these studies reported that the secondary cognitive task significantly decreased postural stability in children with DD (Bucci, Mélithe, Ajrezo, Bui-Quoc, & Gérard, 2014; Vieira, Quercia, Michel, Pozzo, & Bonnetblanc, 2009) or DCD (Cherng, Liang, Chen, & Chen, 2009; Laufer, Ashkenazi, & Josman, 2008; Tsai, Pan, Cherng, & Wu, 2009), supporting the hypothesis that they have a deficit in the automatic integration of postural control.

1.5. Purpose of the present study

The aim of the present study was to assess procedural learning and automatic movements in children with DD, DCD or both, comparing the motor performance of these three groups administering a finger tapping task before and after 2 weeks of training. Learning a skill through repeated practice is commonly recognized to be procedural learning. We therefore looked at whether the behavioral data changed across the learning stages, and used a dual-task paradigm to assess whether automaticity was eventually achieved. Finally, special attention was paid to the DD + DCD group, in order to clarify the role of comorbidity, testing the hypothesis of a possible additive effect (i.e., combination of the deficits induced by each disorder). The present study was therefore designed to address three key issues. First, regarding the procedural/automatization deficit hypothesis, we wanted to ascertain whether children with DCD and/or DD exhibit a deficit in automatization. Second, regarding the hypothesis of shared aetiological bases, we looked for systematic differences in procedural learning between the experimental groups. Third, concerning comorbidity, we examined whether the association of the two disorders has an adverse effect on children’s skills.

2. Materials and methods

2.1. Participants

A total of 67 children (23 girls and 44 boys), aged between 7 years 8 months and 12 years 11 months, took part in the study. The children were recruited either from a dedicated learning disabilities centre (Toulouse Children’s Hospital) or via independent psychomotor and speech therapists. All participants were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal vision, and no history of neurological or psychiatric disorders. Children and parents gave their free and informed consent. All experimental procedures were approved by the local ethics committee (CPP Sud Est V, France).
All the participants underwent the same comprehensive neuropsychological assessment, including tests of intellectual abilities (WISC-IV; Wechsler, 2003), reading skills (Alouette test; Lefavrais, 2005; ODEDYS-2 battery; Jacquier-Roux, Valdois, Zorman, Lequette, & Pouget, 2005), motor skills (Movement Assessment Battery for Children, M-ABC; Henderson & Sugden, 1992), oral skills (EVIP, French version of the Peabody Picture Vocabulary Test-Revised; Dunn, Theriault-Whalen, & Dunn, 1993; EVAC; Flessas & Lussier, 2003; ECOSSE; Lecocq, 1996), attention (CPT-II; Conners & Staff, 2000) and behavior (Child Behavior Checklist, CBCL; Achenbach & Rescorla, 2001).

We recruited children who had been referred as having DCD, DD or both according to the DSM-IV-TR criteria, and applied both sets of diagnostic criteria to each individual. Motor ability was tested using the French version of the M-ABC (Soppelsa & Albaret, 2004), in accordance with the recommendations of the European Academy for Childhood Disability (Blank et al., 2012). Reading disability was assessed with ODEDYS-2 (Jacquier-Roux et al., 2005), in which participants read series of 20 regular words, 20 irregular words, and 20 pseudowords (or nonwords) in order to test their word recognition procedures, and the Alouette French reading test (Lefavrais, 2005). These tests measure accuracy and speed when reading either isolated words or a text, and are generally used to define participants’ reading profiles (phonological, surface, or mixed dyslexia).

Children were placed into one of the three groups (DCD, DD, DD + DCD) according to their motor and reading scores. They were classified as having DCD if their total impairment score (TIS) on the M-ABC was below the 5th percentile, and were deemed not to have a motor impairment if their TIS was above the 15th percentile. Children with a TIS between the 5th and 15th percentiles were excluded. To take both accuracy and speed into account, children were only classified as having DD if they met both of the following criteria: a fluency score for reading isolated words (ODEDYS-2 word or pseudoword reading) 1.5 standard deviations (SDs) below the mean, and second, an Alouette text reading speed score 1.5 SDs below the mean, or a text reading speed score 1 SD below the mean associated with a text reading accuracy score 1.5 SDs below the mean. Children were classified as reading normally if their Alouette reading speed and accuracy scores were 0.5 SD or more above the mean. Children with intermediate results were excluded. Thus, the reading performances of the best reader with dyslexia and the worst nonimpaired reader differed by more than 1.5 SDs for reading speed and by more than 2 SDs for reading accuracy.

In order to obtain groups that were as homogeneous as possible, children with an intellectual disability (<70), SLI or ADHD according to DSM-IV-TR criteria were excluded. More specifically, given the aggravating impact of ADHD on comorbidity (Chaix et al., 2007; Crawford, Kaplan, & Dewey, 2006), all the children were rated by their parents and clinicians on the DSM-IV-TR diagnostic criteria for ADHD (<six inattention and six hyperactive/impulsive symptoms) and were screened on the CPT-II (Conners & Staff, 2000). To reduce the heterogeneity and define more homogeneous groups of participants with developmental dyslexia, also excluded were children presenting a surface dyslexia defined by a specific disorder in learning to read without difficulty for metaphonological tests and/or an exclusive impairment of the addressing/lexical reading route (reading irregular words). In addition, all the children underwent a medical examination to exclude other neurological and psychiatric diseases.

After the test period, two children were excluded owing to an IQ score <70, and six because they failed to complete the experimental protocol (did not attend the post-training session). Our final sample of children for the data analysis therefore comprised the 59 remaining participants (18 girls), including 19 children with DCD (5 girls), 18 with DD (7 girls), and 22 with DD + DCD (6 girls).

2.2. Material and tasks

2.2.1. Material

The finger tapping task was administered on a portable computer. All the auditory and visual stimuli were generated with Presentation software version 12.1 (Neurobehavioral Systems Inc., Albany, CA, USA) that was used to run the experiment and collect the behavioral data. Visual stimuli were displayed on a screen placed 40–50 cm from the children. Participants used their right hand to tap buttons on a response pad (fORP; Current Designs, Philadelphia, PA) that recorded their moves. To minimize the potential differences in amplitude of the subjects’ finger movements between single and dual-tasks, the amplitude of their movements was limited by a foam support.

2.2.2. Tasks

Participants were instructed to perform and memorize a fingers’ tapping sequence task, repeating them continuously and as fast and as accurately as possible for as long as a green cross remained on the screen. The sequence of finger movements was made up of five moves (1–2–1–2–3) using fingers 1 (index), 2 (middle finger) and 3 (ring finger) of the right hand. Movements were self-initiated and self-paced, and no feedback was provided to participants as to whether their finger movements were correct or incorrect.

When a red cross appeared on the screen, the children were asked to relax. Only two auditory stimuli were given: go and stop at the beginning and end of the task period. The finger tapping task was performed in three conditions: (i) as a single task prior to training (pre-training condition); (ii) as a single task after training (post-training condition); and (iii) concurrently with an interference task after training (dual-task condition). For the pre-training condition, the sequence was explained just before the task. Children could familiarize themselves with the task and then practice the sequence. For the post-training condition, the sequence was tested after a two-week training period during which participants practiced the sequence for 3 min twice a day. The practising
was done under direct parental supervision. A practice chart and an hourglass were distributed at the beginning of the practice period, and the chart was checked before the start of the post-training test. All the children without exception performed the practice seriously 3 min twice daily over the 2 weeks. For the dual-task condition, to assess how and if the finger tapping task became automatic, participants were asked to perform it in a dual-task condition. The primary task was therefore the sequence of finger movements (motor task) and the secondary (interference) task was a cognitive task (picture naming). Children were invited to name 12 simple objects (e.g., snail, fireplace, kangaroo) displayed for 5 s on the blank screen one after the other. To ensure that the children could identify and name the objects correctly, the pictures used for this task were chosen from those known to be named without errors in this age range (Deloche et al., 1989). Note that to avoid visual competition between visual stimuli displayed in the picture naming task and the cross displayed in the finger tapping task, in dual-task, the green cross has appeared only at the beginning of the block, simultaneously with the auditory stimulus (go), then disappeared during the picture naming task.

2.3. Procedure

All participants underwent the same thorough neuropsychological assessment in the INSERM unit at the Institute of Brain Sciences in Toulouse (France) during a half-day session. Each testing session included breaks to avoid fatigue and boredom. Participants were tested separately in a quiet environment for all tasks and measures. In addition, all the children underwent a medical examination to exclude ADHD and other neurological and psychiatric diseases.

After the neuropsychological tests, the experimenter explained the protocol and demonstrated the experimental condition. After briefly practising the finger tapping task, each child performed the actual experiment. After familiarization, each child performed a test sequence in six 60-s blocks with alternating rest (30 s) and task (30 s) periods. The children were then asked to practice this sequence for 3 min twice daily for 2 weeks. On day 15, the procedure was repeated and, to assess how automatic the finger tapping task had become, participants also performed it in a dual-task condition. This session began with six blocks of the finger tapping task only, and ended with two blocks in the dual-task condition, where children were asked to perform the finger tapping task (motor task) and the picture-naming task (cognitive task) at the same time.

2.4. Data acquisition and analysis

2.4.1. Clinical acquisition and analysis

The descriptive statistics of the dependent variables were tabulated and examined. The Full-Scale IQ (FSIQ) score on the WISC-IV was included in the analyses as a cognitive variable. The manual dexterity, ball skills and balance subscores, together with the total impairment score of the M-ABC, plus the Alouette text reading accuracy and speed scores, were included in the analyses as motor and reading variables. The omission, commission, hit reaction time, hit reaction time error and perseveration scores of the CPT-II were included as attention variables.

All statistical analyses were performed using IBM SPSS 21.0.0.0. Chi-square tests were used to compare the DCD, DD and DCD + DD groups on age, sex and socioeconomic status. Analyses of variance (ANOVAs) were conducted to investigate the differences between the three groups on the neuropsychological tests. Tukey post hoc tests were performed to compare the means for the three groups. For all tests, a probability level of $p < .05$ was considered to be statistically significant (Huberty & Morris, 1989).

2.4.2. Behavioral data acquisition and analysis

Each key press (correct or incorrect) for each block produced by each participant was recorded with Presentation software. First, we calculated the number of taps for each participant and for each block. Each sequence produced by each participant (chain of five finger movements/five key press) was then compared with the model (previously set chain of the five finger movements/the sequence learned). On this basis, we computed an accuracy index (AI) capturing each participant’s performance. In the pre- and post-training conditions, the task was performed in six blocks, whereas in the dual-task condition, it was performed in just two blocks. The AI for each sequence that was produced was calculated according to the following formula:

$$A_{i} = \frac{S_{i}X}{S_{i}T_{X}}$$

where $S_{i}X$ represents the number of sequences achieved by the participant for the task X and $S_{i}T_{X}$ represents the theoretical number of sequences performed by the participant, given by the formula $S_{i}T_{X} = \sum_{i=1}^{6} [\frac{T_{i}^X}{5}]$ where $T_{i}^X$ represents the number of taps achieved during the block $X$ (1 ≤ $i$ ≤ 6) and $[\cdot]$ the integer part. For example, if a child performed 96, 100, 95, 96, 99 and 92 taps for the six blocks in the task X the theoretical number of sequences $S_{i}T_{X}$ will be calculated by $S_{i}T_{X} = \frac{96}{5} + \frac{100}{5} + \frac{95}{5} + \frac{96}{5} + \frac{99}{5} + \frac{92}{5}$ i.e., $S_{i}T_{X} = 19.2 + 20 + 19 + 19 + 19 + 19 = 114.2$ and finally $S_{i}T_{X} = 114$. As, for this example, the number of correct sequences achieved by the child was, $S_{i}X = 87$ the Accuracy Index is given by $A_{i} = \frac{87}{114} = 0.7632$.
First, a Group (3) × Learning (pre-training, post-training) ANOVA with repeated measures on learning was run on AI, in order to compare the levels of learning achieved by the three groups. Second, a Group (3) × Interference (post-training, dual-task) ANOVA with repeated measures on interference was run on AI to compare the levels of automaticity achieved by the three groups. Because the children were not familiarized with the primary and secondary tasks in combination prior to the formal experiment, Block 1 in the dual-task condition was not included in this statistical analysis. It is important to note here that the level of automaticity did not take account of the number of pictures that were correctly named in the dual-task condition, as there were no errors. Fisher’s LSD post hoc tests were then performed to compare the means for the three groups. For all analyses, the \( p \) value was set at \( p < .05 \), and \( \eta^2 \) was calculated.

For each child, we also calculated the percentage of correct responses to the cognitive task.

3. Results

3.1. Demographic, clinical and neuropsychological results

Demographic and clinical data are set out in Table 1. The chi square test revealed no significant between-group differences in age, sex or socio-economic status. The FSIQ was within the normal range for all three groups, with no significant difference between them. Moreover, the three groups performed similarly on the attention test (CPT-II) and did not differ statistically on sustained attention. As expected, the DD groups with and without DCD differed significantly from the DCD group on all the reading subtests \( (p < .001) \), and the DCD groups with and without DD differed significantly from the DD group on all the M-ABC subtests \( (p < .001) \).

3.2. Behavioral results

The behavioral data are set out in Table 2.

3.2.1. Assessment of learning

The ANOVA revealed a significant effect of learning on AI, \( F(11, 616) = 15.759, p = .000, \eta^2 = 0.220 \) (large effect), but no significant difference between the groups, \( F(2, 56) = 2.112, p = .131 \), and no significant interaction between group and learning, \( F(22, 616) = 1.252, p = .197 \). Whatever the group, the mean AI was lower in the pre-training session \( (0.64 \pm 0.29) \) than in the post-training session \( (0.83 \pm 0.19) \).

Table 1
Demographic and clinical characteristics of the three groups.

<table>
<thead>
<tr>
<th>Child characteristics</th>
<th>DCD only ( (N = 19) )</th>
<th>DD only ( (N = 18) )</th>
<th>DD + DCD ( (N = 22) )</th>
<th>Test-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male ( (41) )</td>
<td>14</td>
<td>11</td>
<td>16</td>
<td>Chi² = .86, df = 2, ( p = .65 )</td>
</tr>
<tr>
<td>Female ( (18) )</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Age in years [mean (SD)]</td>
<td>9.7 (1.3)</td>
<td>10.2 (1.2)</td>
<td>9.8 (1.1)</td>
<td></td>
</tr>
<tr>
<td>WISC-IV FSIQ</td>
<td>103.3 (15.0)</td>
<td>108.0 (14.7)</td>
<td>99.9 (16.1)</td>
<td>( F(2, 56) = 1.38, p = .26 )</td>
</tr>
<tr>
<td>Attention skills</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSM-IV-TR criteria ADH/D</td>
<td>6.7 (1.6)</td>
<td>4.8 (3.5)</td>
<td>5.4 (2.3)</td>
<td>( F(2, 56) = 2.77, p = .07 )</td>
</tr>
<tr>
<td>CPT_Omission (percentile)</td>
<td>54.1 (27.0)</td>
<td>55.9 (26.2)</td>
<td>52.6 (22.2)</td>
<td>( F(2, 56) = 0.04, p = .96 )</td>
</tr>
<tr>
<td>CPT_Comission (perc.)</td>
<td>64.8 (26.9)</td>
<td>70.2 (26.0)</td>
<td>67.7 (27.5)</td>
<td>( F(2, 56) = 0.48, p = .62 )</td>
</tr>
<tr>
<td>CPT_Hit RT (perc.)</td>
<td>53.5 (27.3)</td>
<td>56.4 (26.8)</td>
<td>60.6 (26.1)</td>
<td>( F(2, 56) = 0.38, p = .67 )</td>
</tr>
<tr>
<td>CPT_Hit RT Error (perc.)</td>
<td>56.3 (26.5)</td>
<td>70.4 (23.5)</td>
<td>68.0 (23.7)</td>
<td>( F(2, 56) = 1.17, p = .32 )</td>
</tr>
<tr>
<td>CPT_Perseveration (perc.)</td>
<td>56.0 (23.2)</td>
<td>53.2 (22.1)</td>
<td>59.7 (24.5)</td>
<td>( F(2, 56) = 0.38, p = .69 )</td>
</tr>
<tr>
<td>Motor skills</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M-ABC raw total score</td>
<td>26.6 (6.2)</td>
<td>45.3 (3.5)</td>
<td>24.7 (5.5)</td>
<td>( F(2, 56) = 102.52, p &lt; .001 )</td>
</tr>
<tr>
<td>M-ABC ball skills</td>
<td>5.7 (2.5)</td>
<td>9.0 (1.5)</td>
<td>6.9 (3.7)</td>
<td>( F(2, 56) = 24.51, p &lt; .001 )</td>
</tr>
<tr>
<td>M-ABC balance</td>
<td>8.3 (4.6)</td>
<td>10.2 (1.2)</td>
<td>7.3 (4.2)</td>
<td>( F(2, 56) = 22.70, p &lt; .001 )</td>
</tr>
<tr>
<td>M-ABC manual dexterity</td>
<td>12.7 (2.7)</td>
<td>2.8 (2.7)</td>
<td>10.4 (3.5)</td>
<td>( F(2, 56) = 53.02, p &lt; .001 )</td>
</tr>
<tr>
<td>Reading skills</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM (SD)</td>
<td>0.4 (0.4)</td>
<td>−2.5 (1.0)</td>
<td>−2.5 (1.0)</td>
<td>( F(2, 56) = 68.82, p &lt; .001 )</td>
</tr>
<tr>
<td>CTL (SD)</td>
<td>0.0 (0.8)</td>
<td>−1.5 (0.7)</td>
<td>−1.4 (0.6)</td>
<td>( F(2, 56) = 26.87, p &lt; .001 )</td>
</tr>
</tbody>
</table>

Note: FSIQ = full score IQ; CM = reading speed index; CTL = reading accuracy index; DCD = developmental coordination disorder; DD = developmental dyslexia; DD + DCD = developmental dyslexia plus developmental coordination disorder.

* Significant differences in all motor subtests between DD and DCD with or without DD.

** Significant differences in all reading subtests between DCD and DD with or without DCD.
3.2.2. Assessment of automaticity

In the dual-task condition, regarding the primary task, the ANOVA did not reveal any significant effect of dual-task interference on AI, $F(6, 336) = 1.599, p = .147$. Nor did it reveal a significant interaction between group and interference, $F(12, 336) = 1.124, p = .340$, although there was a significant difference between groups, $F(2, 56) = 3.246, p = .046, \eta^2 = 0.104$ (medium effect). Post-hoc group comparisons using the Fisher’s LSD test showed that DCD group scores were significantly weaker than DD or DD + DCD scores (see Fig. 1).

### Table 2

Mean and standard-deviation of the accuracy index computed for each group of children and each condition.

<table>
<thead>
<tr>
<th></th>
<th>DCD (19)</th>
<th></th>
<th>DD (18)</th>
<th></th>
<th>DD + DCD (22)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
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<tr>
<td><strong>Single-task condition</strong></td>
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<tr>
<td>PreTraining</td>
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<tr>
<td>PreTraining_B1</td>
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<td>0.35</td>
<td>0.64</td>
<td>0.33</td>
<td>0.69</td>
<td>0.32</td>
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<td>PreTraining_B2</td>
<td>0.59</td>
<td>0.35</td>
<td>0.70</td>
<td>0.28</td>
<td>0.67</td>
<td>0.31</td>
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<tr>
<td>PreTraining_B3</td>
<td>0.64</td>
<td>0.35</td>
<td>0.70</td>
<td>0.29</td>
<td>0.65</td>
<td>0.38</td>
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<tr>
<td>PreTraining_B4</td>
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<td>0.32</td>
<td>0.76</td>
<td>0.31</td>
<td>0.59</td>
<td>0.35</td>
</tr>
<tr>
<td>PreTraining_B5</td>
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<td>0.35</td>
<td>0.75</td>
<td>0.28</td>
<td>0.61</td>
<td>0.35</td>
</tr>
<tr>
<td>PreTraining_B6</td>
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<td>0.30</td>
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<td>0.36</td>
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<td>0.26</td>
<td>0.63</td>
<td>0.30</td>
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<td>PostTraining</td>
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<tr>
<td>PostTraining_B1</td>
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<td>0.83</td>
<td>0.26</td>
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<td>0.88</td>
<td>0.24</td>
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<tr>
<td>PostTraining_B3</td>
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<td>0.13</td>
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<td>0.91</td>
<td>0.09</td>
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<td>0.13</td>
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<td>0.13</td>
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<td>0.80</td>
<td>0.17</td>
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<td>0.88</td>
<td>0.11</td>
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<tr>
<td>Mean_DualTask</td>
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<td>0.28</td>
<td>0.84</td>
<td>0.10</td>
<td>0.80</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*Note: DCD = developmental coordination disorder; DD = developmental dyslexia; DD + DCD = developmental dyslexia plus developmental coordination disorder; B = block.*

**Fig. 1.** Mean Accuracy Index for the developmental dyslexia (DD), developmental coordination disorder (DCD) and the developmental dyslexia plus developmental coordination disorder (DD + DCD) groups as a function of blocks. The figure displays means and standard errors for the three learning conditions: in single-task for pre- and post-training sessions and in dual-task.
In addition, concerning the secondary task (interference), all the pictures were correctly named by all the participants without exception, as expected for this age range (Deloche et al., 1989).

4. Discussion

The purpose of the present study was to address the specific issue of procedural/automatization faculties in children with DD and/or DCD, testing performances on a motor sequence learning task before and after learning, when automaticity was presumably achieved. We also tested whether the comorbidity between DD and DCD could have a negative impact on procedural learning and automatization. First, results demonstrated that, despite substantial evidence of procedural learning difficulties in children with DD and/or DCD, they can improve their performance sufficiently to learn a sequence of movements and achieve an advanced level of automaticity. Second, our results indicated between-groups differences (DCD vs. DD and DCD vs. DD + DCD) in procedural/automatization learning abilities. Third, our results unexpectedly suggested that comorbidity has no adverse effect on behavioral performance, especially the acquisition of automaticity.

4.1. Automatization

The present study examined previously untested aspects of procedural memory, specifically the automatization of motor sequences in children with DD and/or DCD. By examining early learning, consolidation and automatization (dual-task paradigm) by means of three practice sessions, our study went beyond earlier research by allowing for a continuous assessment of procedural sequence learning, from acquisition to automatization.

After 2 weeks’ training, the participants’ performances had greatly improved, whichever group they belonged to, showing that children with DCD or DD can learn and improve their performance after proper training with a procedural learning task. This confirms the results of previous studies of DD (Gabay et al., 2012a, 2012b; Kelly et al., 2002; Rüsseler et al., 2006; Waber et al., 2003) and DCD (Lejeune et al., 2013; Wilson et al., 2003). However, as we mentioned above, even if individuals’ performances on a given task improve with practice, they do not necessarily reach the automatization stage (Lang & Bastian, 2002). This stage occurs at the end of the consolidation stage, after a long period of training (Doyon et al., 2009) and several nights’ sleep (Walker et al., 2005), and even if one of the features of automaticity is indeed the quality of performance (especially an improvement in performance and/or resistance to unlearning), this concept is characterized above all by effortlessness (low mental workload) and strength (resistance to interference). The acquisition of automaticity can only be attested to when the task can be performed concurrently with a secondary task with minimal interference (Passingham, 1996). For these reasons, all the participants in the present study practiced the finger tapping task for 2 weeks to allow them the time required for automatization, and performed the task in a dual-task condition to assess whether automaticity had been achieved.

In the dual-task condition, all the participants (i) performed the primary task with minimal interference and without any change in movement parameters (amplitude of the subjects’ finger, hand or arm), and (ii) performed the secondary cognitive task without making any errors (all the pictures were correctly named: participants were not focusing on the primary task to the detriment of the secondary task). Taken together, these results show that there was minimum interference between the finger tapping task and the secondary task. We can therefore argue that all the children were able to perform the finger tapping task with a good level of automaticity.

In line with the automatization/procedural learning deficit model developed by Nicolson and Fawcett (1990, 2000, 2011), we expected the children to perform the motor task (finger tapping) more poorly in the dual-task situation (picture naming). Our results are therefore the first evidence that children with either DD or DCD are able to largely automate a sequence of movements with practice. This result may seem surprising at first. In daily life, children with DCD or DD commonly have less automatic skills (e.g., cycling, writing, reading or tying shoelaces) and have difficulty performing two different tasks at the same time (Legrand et al., 2012; Tsai et al., 2009). In previous studies, when concurrently performing a cognitive and a motor task, children with DD or DCD seemed to prioritize the cognitive task and exhibited poor motor performance (Bucci, Gérard, & Bui-Quoc, 2013; Laufer et al., 2008). The present finding, apparently at odds with these previous studies, has several possible explanations. For a start, studies investigating dual-task performance in DD and DCD have yielded discrepant results. The types of tasks used (motor vs. cognitive), as well as the participants examined (with or without ADHD), could account for some of this inconsistency. Especially, studies exploring the motor performance of individuals with DD or DCD while they perform a secondary task have only observed impairment in some cases, and have therefore suggested that there is a relationship between poor automaticity and ADHD (see, for example, Ramus, Pidgeon, & Frith, 2003; Rochelle & Talcott, 2006). Thus, our exclusion of children with ADHD may have led to a difference between our results and those of previous studies.

Another possible explanation is that previous studies focused almost exclusively on learning compared with a control group (between-groups analysis), and therefore neglected the children’s actual performance (within-groups analysis and intra-individual variability). When measuring automatization, however, participants are their own controls, and their performances in a single-task condition and a dual-task condition are compared. Several criteria may therefore have been omitted, since these previous studies primarily focused on a deficit in automatization in comparison with controls (slower, less accurate), rather than on the ability to achieve automaticity. By including within-groups analysis and comparisons
between single-task and dual-task performances, the present study extended the examination of these abilities in children with DD and DCD (although it did not allow us to specify the quality of automatization as compared to controls).

The third and final possibility is that our choice of task had a decisive influence on our results. Even though the majority of studies to date support the notion of an association between automatization abilities and sequence learning skills tested in dual-task conditions, the nature of this association has yet to be elucidated. Firstly sequential tapping task has little ecological validity for the learning of motor skills in development. In addition, research has shown that the type of secondary task can influence the primary (automated) task to differing degrees (Huxhold, Li, Schmiedek, & Lindenberger, 2006), based on the notion mentioned earlier that the secondary task may shift attention away from the primary (control) task, leading to a change in performance. The tasks we administered in the current study may therefore have been too simple for the children, or maybe also quite meaningless and not representative of real-life tasks, making them too easy to perform (even if it may, however, be noted that picture naming is known to be a difficult task for children with dyslexia according to Jones, Ashby, and Branigan (2012) and Zoccolotti et al. (2012)).

4.2. Shared aetiological bases

In our study, the children with DCD had a particular profile. Their learning outcomes were quite different from those of the other two groups, and they clearly had specific difficulties. Previous studies have provided clear evidence that both disorders (DD and DCD) are characterized by impaired procedural learning and automatic skills (Nicolson & Fawcett, 2011). More specifically, individuals with these disorders are impaired on sequence learning tasks (Bo & Lee, 2013; Lum et al., 2013). To date, however, despite the high frequency of comorbidity, levels of impairment in these two groups have never been compared. The novelty here is that performing the finger tapping task seems to be more complicated for children with DCD. This finding may indicate that there are two different explanations for this impairment. In particular, the relative contribution of different brain structures to procedural learning has been shown to vary according to which procedural task is being performed (motor adaptation vs. sequence learning), as well as to the progress of learning (i.e., changes across the different stages of training). Motor adaptation relies on the corticocerebellar loop, whereas sequence learning involves the corticostriatal loop. Brain imaging studies have highlighted the critical role of the striatum in motor sequence learning. It remains activated from the fast acquisition stage to the consolidation stage (Doyon, Owen, Petrides, Sziklas, & Evans, 1996; Lehericy et al., 2005) while, cerebellar activation decreases rapidly with practice and is no longer detectable in the latter stages of learning (Doyon et al., 2002, 2009). The fact that a significant and specific DCD impairment emerged in sequence learning could suggest a striatal rather than a cerebellar dysfunction. This finding supports the notion of an association between striatal deficits and DCD. The design of the present study did not allow us to specify the nature of this deficit compared with typical children, or to specify whether children with DD show signs of damage, simply supporting the idea that the corticostriatal loop may be more impaired in children with DCD than in children with DD. Even if neuroimaging studies are needed to reinforce this hypothesis, we could supposed that our findings are compatible with the model of Nicolson and Fawcett (2011) about the neural system typography for learning difficulties, since this model includes the prediction that cerebellar functions are impaired in DD and striatal functions in DCD. Our results also show that despite this specific impairment, the children with DCD were able to learn and improve their performance on a motor learning skill. In addition, this improvement appeared to be sufficiently robust to withstand the interference of a secondary task. Taken together, these results are consistent with other studies of DCD showing that these children can improve their performance through repetition and proper training (Revie & Larkin, 1993; Schoemaker, Niemeijer, Reynders, & Smits-Engelsman, 2003). Thus, a variety of approaches have been put forward to address the needs of children with DCD, and there are numerous methods for teaching or improving children’s motor performance. Our finding supports the application of task-oriented approaches, where intervention is focused on task performance, and the interaction between the person, task, and environment is paramount. In these specific approaches, the major assumption is that learning will lead to relatively permanent changes in motor performance (Mathiowetz & Bass Haugen, 1997). Several studies have demonstrated that children with DCD can improve their skill levels by repeating the motor acts in conjunction with specific teaching (Pless & Carlsson, 2000). Our results offer novel evidence in favor of these intervention approaches, showing that intensive practice can improve the performance of participants with DCD.

4.3. Comorbidity

Given the co-occurrence context in neurodevelopmental disorders, it seemed essential to take comorbidity into account. In order to provide an overview of the DD + DCD group, we scrutinized the results of these children particularly carefully, testing the hypothesis of a possible pejorative effect on results. In particular, in line with the procedural learning deficit hypothesis (Nicolson & Fawcett, 2007), we expected the comorbid group to present more behavioral difficulties than the other two groups, as they would experience additive effects at both the behavioral level (i.e., the combination of the deficits induced by each primary disorder) and the neural level (i.e., specific features in both the corticostriatal and corticocerebellar loops). Moreover, previous studies had already shown that the combination of the deficits induced by each disorder can create or exacerbate problems (Flapper & Schoemaker, 2013; Jongmans, Smits-Engelsman, & Schoemaker, 2003) especially for motor skills in DD (Ramus et al., 2003). However, our results were not consistent with these results, as we clearly showed that, with practice, the comorbid group were able to learn, improve and automate a finger tapping task as much as the other
two groups (even if the learning process may have been different between the groups, especially in learning strategies). Given this pattern of findings, we suggest that DD + DCD comorbidity has no adverse effect on behavioral performance (especially the acquisition of automaticity) and does not constitute an aggravating factor.

This finding constitutes a genuine advance and an important basis for further reflection. Interestingly, a similar pattern of results has already been reported for children with a dual diagnosis. Thus, according to Newcorn et al. (2001), the level of impairment in these children may vary according to the type of comorbid association. These authors revealed that although some pathologies appear to aggravate symptoms, others tend to reduce them. In the case of the DD + DCD association, comorbidity may have no particular effect on procedural/automatization abilities.

Furthermore, results from the comorbid group were particularly relevant. This group had a behavioral learning profile very close to that of the DD group, and clearly different from that of the DCD group. Poor performance was found among the children with DCD, but not among those with DD and DD + DCD. The presence of difficulties in the DCD group but not in the DD + DCD group again raises the question of the nature of the motor problem in DD (Fawcett & Nicolson, 2004; Ramus et al., 2003). Should DD + DCD be regarded as an association of disorders, or instead a subgroup of DD or even a separate disorder? By extension, what will happen to individuals with this specific status, given the specific nature of their motor and functional skills, and what therapy and medical care can best help them overcome their difficulties? These are questions that our study did not allow us to answer. However, they indicate the importance of future research on this specific topic.

4.4. Conclusion and limitations

In the special case of DCD and DD co-occurrence, Nicolson and Fawcett’s hypothesis (2007, 2011) raises the question of a shared aetiology. Authors need to ask whether a common basis, notably a procedural learning impairment, can explain their frequent overlap. Within this framework, the question of which kinds of learning profiles are associated with DCD, DD and comorbid cases seems to warrant further study. To answer such a question, the present study featured an initial practice session, a consolidation stage (practice across 2 weeks) and a test of automatization (dual-task condition) using a motor sequence procedural learning task administered to these three populations of children.

Firstly, our results clearly showed that children with DD or DCD can improve their procedural performance and learn a sequence of movements until they are largely automatized. Naturally, the present findings need to be replicated in order to ensure that they can be generalized. It should also be borne in mind that different results could have been obtained if the tasks had been more complex or more ecological (more representative of real-life tasks for children). Indeed, these children may be capable of automatizing a simple finger tapping task, but unable to perform a more complex one. Further studies including a control group with healthy children and a wider range of procedural tasks (linguistic, cognitive, motor, visual or auditory), are also needed to provide normative data at the behavioral levels, especially on this question of automatization.

Secondly, our results indicate that in the acquisition of this skill, children with DCD have specific difficulties, compared with children with DD. Given that sequence learning preferentially involves the striatal loops, our results appear to be connected with Nicolson and Fawcett’s model (Nicolson & Fawcett, 2011), in which the procedural learning impairment, broadly representative of a learning disorder, is specifically attributable to the corticocerebellar circuit in DD, and to the corticostriatal system in DCD.

Thirdly, interestingly, our study seems to support the idea that the finger tapping task can be learned, improved and highly automatized, not only by children with a single disorder, but also by children with a dual diagnosis. Moreover, the motor skills of this group appeared to be preserved and quite similar to those of the DD group. This group did not perform as poorly as the DCD-only group, questioning the status of the motor impairments in DD. Identifying the factors that contribute to the different learning and performance profiles in DCD and DD + DCD is undoubtedly difficult, but appears to be an important step toward providing children who have learning disabilities with individualized intervention programmes.

Funding

This research was supported by Toulouse University Hospital (Hôtel-Dieu, 2 rue Viguerie, 1052 Toulouse Cedex 9, France) and funded by a Grant (Protocol No. 1013502N’ID-RCB 2010-A00909-30). This study complied with the Declaration of Helsinki, the ethical guidelines set out in the French law n°2004-806 of 9th August 2004, and respected best clinical practice (24th November 2006).

Conflict of interest

The authors report no conflicts of interest.
Acknowledgments

We would like to thank all the participating families, all the children, the parents’ associations and the referring clinicians. The authors also thank Elizabeth Portier for her careful checking of English language and the reviewers for their constructive comments.

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