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Dissociation between online and offline learning in developmental dyslexia

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Most studies investigating procedural learning in developmental dyslexia (DD) have focused on the acquisition stage, ignoring later stages involved in the process of skill learning. The current study examined sequence learning among DD and control groups in two sessions. Both groups completed a sequence-learning task over a first session (online learning) and a second session 24 hours later (offline learning). While both groups showed improvements in performance during offline learning, only the control group showed improvements in performance during online learning. Moreover, the DD group differed from the control group in their ability to recover from the introduction of a different sequence.

Keywords: Developmental dyslexia; Procedural learning; Sequence learning; Memory Consolidation; Automaticity.

Developmental dyslexia (DD) is defined as a specific functional failure to acquire age-appropriate reading skills in otherwise normally developing children (Curtin, Manis, & Seidenberg, 2001; Stanovich, 1988; Vellutino, 1979). Although DD is a neurological disorder, the underlying biological and cognitive causes of the reading deficits are still extensively under debate (Ramus, 2003). One of the main theories on DD, the *cerebellum deficit hypothesis* (Nicolson, Fawcett, & Dean, 2001) attempts to explain why reading impairment is often accompanied with other nonlinguistic and sensory–motor symptoms. According to this theory, a cerebellar dysfunction is the cause of developmental dyslexia, leading to difficulties in the acquisition and automatizing of new skills such as reading. According to this view (Nicolson & Fawcett, 2008), characteristics of automatic performance may be seen as the *quality* of performance (speed and accuracy), *effortlessness* (low input of conscious resources), and *strength* of automatization (resistance to interference and to unlearning). This framework has been lately modified to its current form, *specific procedural learning difficulties* (SPLD; Nicolson & Fawcett, 2007) according to which dyslexics have deficits in the procedural learning system that arise from damage to one of the brain areas related to this system (such as the prefrontal cortex around Broca's area, parietal cortex, and subcortical structures including the basal ganglia and the cerebellum). Since the cerebellum has been shown to be involved in the acquisition of new skills as well as in reading (see Vlachos, Papathanasiou, & Andreou, 2007, for a review), previous studies examining the cerebellum deficit hypothesis had employed skill-learning tasks to examine the performance of individuals with DD. Before introducing studies of skill learning in DD, the topic of skill acquisition is briefly reviewed.

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The time course of skill learning

A recent body of research suggests that the passage of time may play a crucial role in the acquisition of new skills. The process of skill acquisition begins with the first exposure to a task. This phase requires a training interval involving repeated engagement with the procedure being learned (Rattoni & Escobar, 2000). This phase is termed the *acquisition phase* or *fast learning phase* and is accompanied by fast improvements in performance that can be seen over seconds or minutes (*online learning*). The improvements during initial task practice follow a curve, and performance gradually reaches an asymptote. Upon successful completion of acquisition, a slow learning phase is believed to occur, in which slow improvements in performance may be seen within hours to days. This phase involves a consolidation, whereby new memory traces become increasingly less susceptible to interference (Walker, 2005). Consolidation in the procedural domain relates to two different behavioral stages: (a) *consolidation-based stabilization* (CBS) and (b) *consolidation-based enhancement* (CBE). CBS can be described as the reduction in fragility of a memory trace after the acquisition of a novel skill (Robertson, Pascual-Leone, & Miall, 2004). Evidence for such a process can be seen in the loss of an acquired skill if an individual immediately attempts to acquire a similar skill. However, if time elapses between the acquisition of the first skill and training in the second skill, the amount of interference decreases (Goedert & Wilingham, 2002). This process, in which the memory traces become more stable, takes place in a time frame of six hours after the initial acquisition. At this stage, behavioral performance is maintained and is not improved. Nevertheless, different patterns of regional brain activation can be developed, indicating a change in the neural representation of the skill (Shadmehr & Holocomb, 1997).

Further behavioral improvement can be seen in the additional CBE stage, also termed *offline learning*. During this stage, in the absence of any further rehearsal or experience, additional learning may take place after sleep. These additional improvements are accompanied by synaptic and structural changes in the brain. The brain areas that are involved in the time course of skill learning are a matter of debate in the research literature. Doyon and Ungerleider (2002), for example, suggested that cerebral plasticity during skill learning depends on the stage of learning (fast, slow, etc.), as well as on the nature of the task: whether individuals are learning a new sequence of movements (motor sequence learning) or learning to adapt to environmental perturbations (motor adaptation). In the first stage of learning, both tasks recruit similar cerebral structures: striatum, cerebellum, and motor cortical regions, in addition to prefrontal and parietal areas and limbic areas. In later stages of learning (consolidation, slow learning phase, etc.), the tasks vary in the use of cerebellar functioning that is required for successful completion. Motor adaptation no longer requires the striatum for the retention and execution of the acquired skill. Instead, regions representing the skill now include the cerebellum and related cortical regions. In contrast, a reverse pattern of plasticity is thought to occur in motor sequence learning, such that with extended practice, the cerebellum is no longer essential, and the long-lasting retention of the skill is now believed to involve representational changes in the striatum and associated motor cortical regions. This model was verified in a number of behavioral, lesion, and neuroimaging studies (see Doyon & Benali, 2005, for a review).

Skill learning in DD

A number of studies sought to examine the cerebellar deficit hypothesis in individuals with DD using serial reaction time task (SRT; Nissen & Bullemer, 1987). In this task, participants are presented with a visual stimulus in one of several discrete locations and are requested to make a rapid key press corresponding to the stimulus location. Unknown to the participants, the stimuli appear in a repeated sequence, and learning of the sequence is measured as a decrease in reaction time across blocks or as a difference between reaction time to sequence and random (or a different sequence) blocks (Seger, 1994). Despite the clear evidence of learning, participants are neither able to report the underlying pattern nor able to recall the sequence (Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993). Thus, this kind of sequential learning has been referred to as implicit learning (see Berry & Dienes, 1993; Seger, 1994; Shanks & St. John, 1994, for reviews).

Several studies have revealed impairment in sequence learning among adults with DD as measured by the SRT task (J. H. Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). Other studies have reported intact sequence learning among individuals with DD (Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006). Specifically, Vicari et al. and Stoodley et al. found that DD children did not show a transfer in the

SRT, nor a reduction in reaction time (RT) when the repeated sequence was introduced. Howard et al. and Menghini et al. reported only a lack of transfer in the SRT in DD adults compared to normal readers. Finally, Rüsseler et al. and Kelly et al. showed that DD adults exhibited a decrease in RT during learning the repeated sequence, while showing an increase when a different/random block was introduced. This inconsistency might be attributed to differences in the experimental design, sampling, procedures being used, and so on. Indeed, previous research on the SRT task indicated several parameters that can affect implicit learning, among them the length of the sequence being used (D. V. Howard & Howard, 1992; Pascual-Leone et al., 1993), the length of response–stimulus interval (Destrebecqz & Cleeremans, 2001), the structure of the sequence (Stadler & Neely, 1997), the use of random/different blocks (Vaquero, Jiménez, & Lupiáñez, 2006), as well as the amount of training. The studies cited earlier, for example, differ greatly in these parameters, which make it difficult to compare their results directly and to reach a clear conclusion regarding SRT in DD. Moreover, Orban, Lungu, and Doyon (2008) claim that the major limitation of these studies is the focus on incidental learning in the fast acquisition phase using the SRT task, while disregarding later stages believed to be involved in the process of skill acquisition.

The present study investigated skill learning using the SRT task in two groups: a group of adults with DD and a group of controls. In order to assess changes in performance across initial and later stages of learning, participants were tested in two experimental sessions. Participants completed the SRT over one practice session (online learning) and a second session 24 hours later (offline learning).

One of the advantages of using the SRT task to study learning processes is that this task allows the use of several measures: first, the learning rate, also termed *online learning*, which is reflected by the reduction in RT across training blocks (Blocks 1–3) when the same sequence is presented repeatedly. This measure reflects generalized skill learning (e.g., mapping the specific response to the specific stimulus position; Ferraro, Balota, & Connor, 1993; Knopman & Nissen, 1987). Second, indirect sequence learning (also termed *transfer*) is measured as the increase in RT when a block with a random or different sequence is presented, compared to the previous repeated sequence. Third, consolidation, also termed *offline learning*, as measured by a decrease in RT after sleep in the first block of the second meeting compared to the last block of the first meeting. Fourth, the recovery phase is measured by a decrease in RT when returning to the repeated sequence after introducing a different sequence. Lastly, explicit memory of the sequence is measured by the "generate" task, in which the participant is asked to predict the next position of the stimuli.

Online learning in DD has been investigated in many previous works (see Folia et al., 2008, for a review). The main focus of the current work was to examine offline learning and consolidation processes in DD. Orban et al. (2008) stated that in order to assess consolidation and slow learning phases in DD, "one will have to ensure that the subjects with dyslexia overcome their shortcomings during the early learning phase" (p. 168). Previous research demonstrated that learning Sequence B immediately after Sequence A (in the first stage of learning using SRT task) impaired offline learning in normal subjects (Goedert & Willingham, 2002). In addition, it was demonstrated that patients with cerebellar stroke showed a deficit in motor sequence learning when interrupted by the presentation of a different block (Dirnberger, Novak, Nasel, & Zehnter, 2010). If, indeed, DD individuals suffer from a deficit in cerebellar function (Nicolson et al., 2001), the presentation of a different block might harm their ability to learn the repeated sequence in the SRT task. It was also demonstrated that DD individuals are impaired in executive functions, which relate to cognitive flexibility and susceptibility to interference (Hedden & Yoon, 2006). The studies cited above indicate that introducing a different sequence (at first session) might interrupt DD learning to a greater extent than it would for normal readers and result in greater deficient offline learning for DD. Mindful of Orban's et al. views, the current study aimed to maximize initial acquisition of the motor skill for DD. Therefore, a different block, taken as an indication of specific sequence learning, was introduced only at the second session of learning.

Doyon and Ungerleider's model (2002) suggests that in motor sequence learning, the cerebellum, striatum, and motor cortical regions, in addition to prefrontal and parietal areas and limbic areas, are believed to be involved in the first stages of learning, while in later stages, the cerebellum is no longer essential. Using positron emission tomography (PET), it has been demonstrated that individuals with DD showed abnormal cerebellar brain activation while performing a sequence of finger movements (Nicolson et al., 1999). Furthermore, recent research has found that the right cerebellum is the brain region that discriminates best between normal readers and individuals with DD (Pernet, Poline, Demonet, & Rousselet, 2009). Considering these results and Doyon and Ungerleider's suggestions, one might predict that individuals with DD will present a deficit during the initial stages of motor sequence learning (related to cerebral circuits) rather than later stages of motor sequence learning (related to striatum circuits).

METHOD

Twenty-four university and college students were selected for two experimental groups: a group with DD (4 male, 8 female) and a control group (1 male, 11 female). The mean age was $M = 24.8$ years and $M = 23.5$ years in the DD and control groups, respectively. All participants with DD had a well-documented history of developmental dyslexia independently assessed by an educational psychologist. Participants with DD were paid 70 NIS (~$20) for participating in the experiment, while the controls received course credit for participation. This difference might influence the groups' motivation differently. Nevertheless, both groups were informed prior to their participation that regardless of their performance they would receive the reward. All participants were native Hebrew speakers with no reported signs of sensory or neurological deficits/attention-deficit/hyperactivity disorder (according to the American Psychiatric Association, 1994) and came from families of middle to high socioeconomic status.

All participants underwent a series of cognitive tests in order to evaluate their general intelligence (as measured by the Raven–Standard Progressive Matrices, SPM, test; Raven, Court, & Raven, 1992), verbal working memory (as measured by Digit Span from the Wechsler Adult Intelligence Scale, WAIS–III; Wechsler, 1997), and rapid naming (Rapid Automatized Naming; Denckla & Rudel, 1976). Moreover, participants completed a single-word reading test and nonword reading test (Schiff & Kahta, 2009a, 2009b) to measure reading accuracy and speed abilities. The two groups did not differ in age or cognitive ability, but, as expected, the DD group performed worse than the control group on tests of single word and nonword reading as well as on rapid automatized naming (RAN) tests and verbal working memory. The group with DD was composed of 12 students at or below the 50th percentile in both the accuracy and the speed measures (see Table 1).

TABLE 1
Cognitive and literacy scores for control and DD groups samples

	Group	
Subtest	*Control*	*DD*
Age (years)	24.83	23.58
Raven	56.166	55.083
Digit span*	12	8.66
Letter naming*	19.166	23
Digit naming*	17	21.583
RT word reading**	83.250	61.50
Acc word reading**	105.916	93.666
RT nonword reading**	55.085	28
Acc nonword reading**	36.500	20.667

Note. DD = developmental dyslexia; RT = reaction time; Acc = accuracy. The values of RT for word and nonword reading subtests represent the number of correct responses that participants made in 45 seconds. The values of Acc for word and nonword reading subtests represent the number of correct responses that participants made.
$^{*}p < .05$; $^{**}p < .01$.

Stimuli and design

Serial reaction time task

In this task, a red light appeared in one of four squares (3.3 × 3.3 cm) arranged horizontally on the computer screen. Participants were given the following instructions: "A red X will appear in one of the four squares on the screen. Using the fingers of your dominant hand, press the key that corresponds to the position of the red X as fast as possible. In other words, you have to respond with the keys (M, <, >, ?) respectively, for the red X that appears from the left-most to the right-most position." The red X position appeared in a 12-trial sequence of repetitions. Nine repetitions of this sequence (i.e., 108 trials) made up one block. In order to rule out the possibility that a specific sequence will lead to learning, half of the participants in each group were trained in one sequence (342312143241) and the other half in another sequence (341243142132). The sequences were balanced for location frequency (each location occurred three times), transition frequency (each possible transition from one location to a different one occurred once), reversal (e.g., 1–2–1) frequency (one in each sequence), repetitions (no repetitions in either sequence), and rate of full coverage (see Reed & Johnson, 1994). The only difference between the sequences was in their second-order conditional structure. For example, 3–4 was followed only by a 2 in the first sequence but only by a 1 in the second sequence. The next target spatial location appeared on the screen within 5 seconds or as soon as a response was made, whether the response was correct or incorrect. Reaction time (RT) was defined as the time from onset of the stimulus to pressing of the response key. Reaction time was recorded automatically by the computer for correct responses; only incorrect responses were recorded as errors. Stimulus presentation and the recording of response time and accuracy were controlled by a computer program (Super Lab). The response–stimulus interval (RSI) was 0 ms in order to hamper the development of explicit awareness (Destrebecqz & Cleeremans, 2001). In the first session, participants were presented with three blocks, with a 45-second rest between blocks. The starting point of the repeating sequence was different in each block in order to minimize the likelihood of subjects' gaining declarative knowledge while performing the task (Willingham, Salidis, & Gabrieli, 2002). In the second session (24 hours after the first), participants were presented with three blocks. The first had the same sequence as that in the first session, the second block had a new sequence, and the last block had the same sequence as that in the three blocks in the first session. Preliminary results with eight normal readers indicated that three blocks of a repeated sequence were sufficient to elicit offline learning. Comparison of the mean of medians of the third block of the first session ($M = 493.32$) to that of the first block of the second session ($M = 413.49$) reached a significant decrease in reaction time, $t(7) = 7.82$, $p < .001$.

Explicit knowledge

Upon completion of the task, participants were debriefed promptly and were asked: "Did you notice anything different about the tasks?"; "Was there a pattern or sequence present at the task?"; and "If you noticed any sequence, could you try generating it?" After that, participants were informed that they were presented with a repeated sequence in the first three blocks and in the fourth and sixth block. They were presented with a series of stimuli and were asked to push the response button in the location where they predicted the next stimulus would appear according to the sequence presented during the task. Following the response, whether right or wrong, the target moved to the next right position. The participants were told that in this task they would not be timed and should focus on being correct rather than being fast. The number of correct positions selected out of the position sequence was recorded. This task was designed to test the explicit memory of the SRT task sequence. It should be noted that the ability of the generate task to measure explicit knowledge has been criticized (Perruchet & Amorim, 1992), yet it is an acceptable measurement for it.

RESULTS

The mean of the median (of a 12-item sequence) RT per block (i.e., 108 trials) was analyzed. In addition the number of errors (i.e., incorrect responses) was analyzed. Figure 1 presents the mean of the median RT as a function of blocks of the SRT task for both groups.

The groups (DD and control) were compared on different learning measures of the SRT task: First is the *learning rate (online learning)* across the three blocks of the repeated sequence in the first session; second is the effect of overnight delay by comparing the first block of the second session to the last block of the first session, which would indicate

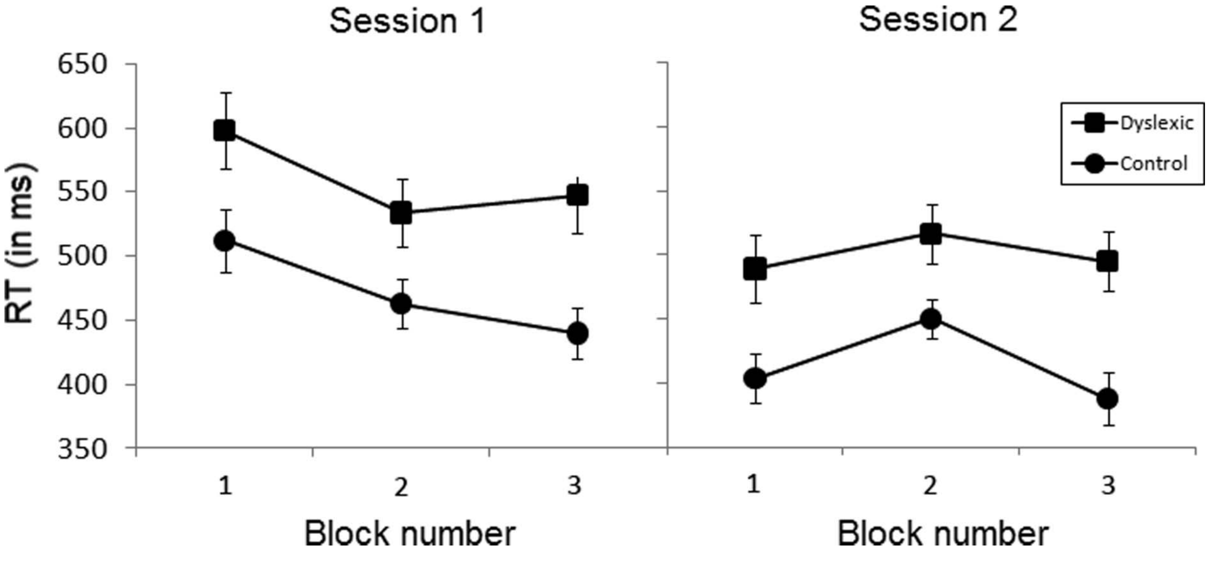

Figure 1. Mean of the median RT (reaction time) of the DD (developmental dyslexia) and control groups in the first and second sessions in the SRT (serial reaction time) task.

consolidation (offline learning); third is the *transfer* by comparing the repeated sequence (i.e., first block, second session) and the different sequence (i.e., second block, second session). The *recovery from interference* was also assessed by comparing a different sequence (i.e., second block, second session) to the repeated sequence (i.e., third block, second session). In addition, the groups were compared on the generate task, which reflects *explicit knowledge* of the repeated sequence.

Learning rate: Blocks 1–3 (first session)

The mean of median reaction time of the two groups in all three blocks of the first session was submitted to a mixed-design analysis of variance (ANOVA) with group as a between-subjects factor and learning trials as a within-subjects factor. Overall, DD group was slower than the control group, $F(1, 22) = 6.358$, $MSE = 21{,}871$, $p < .05$, $\pi^2_{\text{p}} = .22$ ($M = 471$ ms, $SD = 70$ ms for the controls; $M = 559$ ms, $SD = 97$ ms for DD). There was also a main effect for learning, as indicated by a decrease in the RT across the three learning blocks in the first session, $F(1, 22) = 48.779$, $MSE = 908$, $p < .01$, $\pi^2_{\text{p}} = .31$ ($M = 555$ ms, 598 ms, 493 ms, $SD = 101$ ms, 87 ms, 101 ms, respectively). In addition, the group by learning interaction reached significance, $F(1, 22) = 3.55$, $MSE = 908$, $p < .05$, $\pi^2_{\text{p}} = .13$. Further analysis revealed that controls and DD group showed a similar decrease in the RT to the second block as they did to the first block, $F(1, 22) = 1.178$, $MSE = 544$, $p < .1$ ($M = 49$ ms, $SD = 34$ ms for the controls; $M = 64$ ms, $SD = 31$ ms for DD). Nevertheless, while the control group showed significant reduction in the RT to the third block compared to the second block, $F(1, 11) = 10.214$, $MSE = 305$, $p < .05$, $\pi^2_{\text{p}} = .48$ ($M = 22$ ms, $SD = 24$ ms), DD group showed a significant increase in RT to the third block compared to the second block, $F(1, 11) = 4.831$, $MSE = 237$, $p = .05$, $\pi^2_{\text{p}} = .3$ ($M = 13$ ms, $SD = 21$ ms).

Consolidation: Block 3 (first session) versus Block 1 (second session)

There was an overall decrease in the RT to the first block (second session) compared to the last block (first session), $F(1, 22) = 40.37$, $MSE = 669$, $p < .01$, $\pi^2_{\text{p}} = .56$ ($M = 47$ ms, $SD = 37$ ms). There was also a main effect of group, in that the DD group was overall slower than the control group, $F(1, 22) = 8.302$, $MSE = 13{,}436$, $p < .05$, $\pi^2_{\text{p}} = .27$ ($M = 36$ ms, $SD = 26$ ms for the controls; $M = 58$ ms, $SD = 44$ ms for DD). The consolidation by group interaction did not reach significance, $F(1, 22) = 2.180$, $MSE = 669$, $p > .05$. This effect shows offline learning for both groups. In order to examine the measure of consolidation more precisely and reduce the influence of online learning, an additional ANOVA was conducted. In this analysis, the last 48 trials of the first session were compared to the first 48 trials of the second session. This analysis confirmed the results and demonstrated that both groups showed similar offline learning. There was a main effect for group, $F(1, 22) = 8.7$, $MSE = 14{,}814$, $p < .05$, $\pi^2_{\text{p}} = .28$, and a main effect of block, $F(1, 22) = 23.22$, $MSE = 1{,}711$, $p < .05$, $\pi^2_{\text{p}} = .51$. There was no interaction between those variables, $F(1, 22) = 1.728$, $MSE = 1{,}711$, $p > .05$.

Transfer: Block 1 (second session) versus Block 2 (second session)

There was an overall increase in the RT to the different sequence (Block 2, second session) compared to the repeated sequence (Block 1, second session), $F(1, 22) = 24.024$, $MSE = 682$, $p < .01$, $\pi^2_{\text{p}} = .52$ ($M = 36$ ms, $SD = 37$ ms). The DD group was also slower overall as indicated by main effect for group, $F(1, 22) = 6.625$, $MSE = 10{,}381$, $p < .05$, $\pi^2_{\text{p}} = .23$ ($M = 380$ ms, $SD = 82$ ms for the controls; $M = 475$ ms, $SD = 101$ ms for DD group). The interaction between these variables did not reach significance, $F(1, 22) = 1.648$, $MSE = 682$, $p > .05$.

Recovery from interference: Block 2 (second session) versus Block 3 (second session)

The recovery effect, $F(1, 22) = 30.924$, $MSE = 680$, $p < .01$, $\pi^2_{\text{p}} = .58$ ($M = 41$ ms; $SD = 41$ ms), reached significance, as did the group effect, $F(1, 22) = 9.232$, $MSE = 9{,}745$, $p < .05$, $\pi^2_{\text{p}} = .29$ ($M = 481$ ms, $SD = 57$ ms for the controls; $M = 527$ ms, $SD = 80$ ms for the DD group). The interaction between those variables was also significant, $F(1, 22) = 7.458$, $MSE = 680$, $p < .05$, $\pi^2_{\text{p}} = .25$. This pattern indicates that the DD group needs a longer time in order to recover from learning of a different sequence than does the control group. Further analysis revealed that both groups showed a decrease in the RT to the repeated sequence (Block 3, second session) compared to the different sequence (Block 2, second session), $F(1, 11) = 21.175$, $MSE = 1{,}104$, $p < .01$,

$\pi^2_p = .65$ ($M = 62$ ms, $SD = 46$ ms), for the control group, and $F(1, 11) = 10.636$, $MSE = 256$, $p < .05$, $\pi^2_p = .49$ ($M = 21$ ms, $SD = 22$ ms), for the DD group.

Explicit knowledge

The control group and the DD group did not differ significantly in the number of correct sequence positions generated (45%, 36%, of correct response for the control and DD groups, respectively), $F(1, 22) = 2.015$, $MSE = 16$, $p > .1$.

SRT errors

The only effect found in the analysis of errors was in the recovery measure: The recovery main effect was significant, $F(1, 22) = 6.784$, $MSE = 0.022$, $p < .05$, $\pi^2_p = .23$, and the group main effect was marginally significant, $F(1, 22) = 3.122$, $MSE = 0.021$, $p = .091$, indicating that the control group was overall more accurate than the DD group. Thus there was no trade-off between reaction time and accuracy.

Relations between learning measures

Learning rate and consolidation were not significantly correlated in either group: control group, $r(1, 12) = -.10$, $p > .05$; DD group, $r(1, 12) = -.10$, $p > .05$. It has been demonstrated that a minimal amount of training is required in order to elicit consolidation (Hauptmann, Reinhart, Brandt, & Karni, 2005). Our work in conjunction with previous studies demonstrates that the amount of learning does not modulate consolidation (Walker et al., 2003).

DISCUSSION

The present study explored motor sequence learning in DD in two separate sessions. This procedure enabled tapping changes in performance believed to occur in initial and later stages of skill learning. An atypical skill learning process has been detected among dyslexic readers compared to their normal reading counterparts. First, individuals with DD showed a deficit in the first stage of learning. That is, while in the first session, the control group showed a constant decrease in RT across blocks, with the lowest RT in the last block, the group of DD had an increase in RT at the last block. These results are consistent with previous studies, which revealed a deficit in the acquisition stage of sequence learning in DD adults (J. H. Howard et al., 2006; Menghini et al., 2006; Stoodley, Harrison, & Stein, 2006) and children (Vicari et al., 2005; Vicari et al., 2003). This online deficit may be attributed to differences in the processes involved in sequence learning. These processes include the "reaction-time-task learning" as defined by Knopman and Nissen (1987), also termed "generalized skill" (Ferraro et al., 1993). This process is regarded as related to proficiency in execution of the RT task (e.g., mapping the specific response to the specific stimulus position). Another process is the "sequence-specific learning" in Knopman and Nissen's terms, or "implicit learning" as defined by Ferraro et al., which reflects implicit learning of the specific sequence in which stimuli were presented. It is argued that individuals with DD failed to show significant decrease in RT during the first session since they were impaired in general learning ability. In the current experiment, three training blocks of a repeated sequence were provided, avoiding particularly the presentation of a different sequence (which is used as a measure of sequence learning) in the first session. This procedure was adopted since DD exhibited a deficit in executive function (Brosnan et al., 2002; Poljac et al., 2010), which makes them more susceptible to interference. Therefore, it was reasonable to believe that DD consolidation might be differentially affected by introducing a different sequence in the first phase of learning. Additionally, introducing a different sequence in the first session would not allow direct measurement of consolidation processes, since it might be confounded with DD deficit to recover from the introduction of a new sequence. It should be noted that DD sensitivity to the introduction of a different sequence was observed in our work. DD recovery ability from the introduction of a new sequence at the second session was significantly lower than that of controls. This reduced recovery ability would surely influence DD performance if a random block was introduced at the first session. Although general learning ability could not be dissociated from sequence learning in the DD group in the first session, the fact that individuals with DD learned the specific sequence (as can be demonstrated in the second session) implies that the specific sequence learning ability is not impaired. Rather, it is possible that these individuals have a deficit in general learning ability. It seems that the practice given to the individuals with DD in the first session was not sufficient to produce a reduction in reaction time, as was found among the controls during the initial stage of learning. Automaticity is a central concept in the field of psychology. Despite its central nature, there is no consensus about the definition of automaticity, nor regarding its measurement (see Moors & De Houwer, 2006, for a review). Logan (1988), for example, explained the development of automaticity as a transition from algorithm computation (or multistep memory retrieval) to single-step memory retrieval. A different view states that a process is automatic if such a process runs without conscious monitoring (Perlman & Tzelgov, 2006). According to Nicolson and Fawcett (2008), increase in performance speed during acquisition of a new skill may reflect the quality of performance and may be a characteristic of automatic performance. Thus, it could be argued that individuals with DD did not reach the same level of automatic performance as the controls. This finding is in accordance with previous research indicating that the initial performance among individuals with DD while performing a keyboard game was deficient as compared to that of normal readers (Nicolson & Fawcett, 2000).

With regard to later stages of learning, the results revealed that individuals with DD exhibited intact sleep-based consolidation. This implies that they can benefit from offline processes similar to normal readers. It also appears that the initial deficit in online learning detected among individuals with DD does not necessarily impair their ability to improve performance through offline processes. The results showed a clear behavioral dissociation between online and offline learning among individuals with DD. This dissociation is in accordance with previous research that demonstrated an inverse dissociation between online and offline learning among aging adults (Brown, Robertson, & Press, 2009) and schizophrenic patients (see Manoach & Stickgold, 2009, for a recent review). Specifically, it was found that those individuals were impaired in their ability to learn a skill during offline processes while showing preserved online learning. The present results are also in accordance with Walker et al.'s (2003) work among healthy individuals, which found that practice and sleep-dependent aspects of learning on sequence learning are uncorrelated and appear to reflect discrete processes of motor learning. Similarly, the results of the present study showed that practice-dependent (online) learning and sleep-dependent (offline) learning were not correlated in either the control or the DD groups. It should be noted that there was no measurement for the quality and quantity of sleep, which might influence consolidation processes. Yet all participants reported having a normal night's sleep between the sessions.

As mentioned earlier, the current study revealed an interesting defect in recovery from interference in the second session among individuals with DD. This retroactive interference would imply that individuals with DD are more prone to interference than are normal readers. Susceptibility to interference can be seen as an indicator of the strength of automatization of a new skill (Nicolson & Fawcett, 2008). It could be argued, based on our results, that although individuals with DD can improve their skill by offline processes, the strength of that skill is more fragile and less automatized than that of normal readers. Such an explanation accords with previous research pointing to difficulties of children with DD in automatizing new skills (Nicolson & Fawcett, 2008). The difficulty in recovery from interference evident among the DD group may also be accounted for by an impaired cognitive flexibility. Cognitive flexibility relates to the ability of the cognitive system to dynamically activate and modify cognitive processes in response to changing task demands and context factors (Deák, 2003). Thus, a deficit in this mechanism might cause the observed impaired performance among individuals with DD, in their attempt to return to the sequence being learned. Impaired cognitive flexibility is related to executive functions, which have also been found to be deficient in the DD population (Brosnan et al., 2002; Poljac et al., 2010).

In conclusion, individuals with DD failed to exhibit a normal online learning curve, though the offline processes seemed to remain intact. Furthermore, this group showed difficulties in the ability to recover from the introduction of a different sequence and appeared to suffer from retroactive interference.

The cerebellum deficit hypothesis (Nicolson, Fawcett, & Dean, 2001) may account for the findings of the present study. According to this framework, individuals with DD have a deficit in the acquisition and automaticity of new skills, which stems from a deficit in cerebellar functions. The present results are also in accordance with Doyon and Ungerleider's (2002) model regarding neural plasticity during skill learning. According to this model, sequence learning involves both the cerebellum and the striatum in the first stage of learning, while only the striatum is believed to be essential in later stages of learning. Since individuals with DD exhibit abnormal cerebellar engagement (Nicolson et al., 1999), one would predict deficits in the initial stage of sequence learning but not in later stages. The present study confirms this hypothesis.

Karmiloff-Smith (1992) suggested that cognitive development depends on procedural learning that starts with the initial phase of setting up a new stage of representation. A deficit at this initial stage could inhibit new skill acquisition such as reading. More recently, Hill, Hogan, and Karmiloff-Smith (2007) reformulated the importance of sleep and consolidation processes as a precondition of learning and cognitive development in childhood. This research reveals a deficit in initial online learning stages and high vulnerability to interference among individuals with DD, while offline processes seem to be intact. Intervention programs for DD usually contain mixed training for different complex skills, such as training on phonological awareness, word identification, writing, and spelling (Scanlon & Vellutino, 1997). It is suggested that future intervention programs concentrate upon establishing one skill at a time and avoid shifting between skills. Using this procedure would enable DD individuals to learn the skill without interference, thus enabling consolidation processes to take place and fostering the quality of performance.

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