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Performance of Children With Developmental Dyslexia on Two Skill Learning Tasks—Serial Reaction Time and Tower of Hanoi Puzzle: A Test of the Specific Procedural Learning Difficulties Theory

Eli Vakil, PhD[1], Michal Lowe, MA[1], and Carol Goldfus, PhD[2]

Abstract

Among the various theories proposed to explain developmental dyslexia (DD), the theory of specific procedural learning difficulties has gained certain support and is the framework for the current research. This theory claims that an inability to achieve skill automaticity explains the difficulties experienced by individuals with DD. Previous research on automaticity and DD has exhibited methodological issues such as a failure to test a range of skills. The current study broadens previous findings by delineating various reading skills correlated with several aspects of skill acquisition. Furthermore, the study utilizes two nonverbal tasks that reflect distinct types of skills: Serial Reaction Time (SRT) and the Tower of Hanoi Puzzle (TOHP). A total of 53 children aged 11 to 13 participated in the study, of whom 23 were children with DD and 30 were controls. Participants completed a test battery that consisted of reading tests, the SRT, and the TOHP. Results show no differences in learning rate between individuals with or without DD, although individuals with DD performed both tasks at a slower rate. Correlations were identified between a number of reading measures and measures of skill acquisition, expressed primarily in individuals with DD. Implications are examined in the discussion.

Keywords

developmental dyslexia, SRT, TOHP, procedural learning

Developmental dyslexia (DD), also referred to as specific reading disability, affects 5% to 12% of school-aged children. Characteristics of this disability include pervasive difficulties in word recognition, phonological decoding, and spelling, though typical IQ and development are exhibited in other realms (Lyon, 1995; Vellutino, Fetcher, Snowling, & Scanlon, 2004). Literature regarding DD etiology offers numerous theories, yet remains inconclusive. Theories that have aroused a great deal of interest describe deficits in visual processing (Breitmeyer, 1989; Lovegrove, Martin, & Slaghuis, 1986; Stein, 2001), auditory processing (Tallal, 1980), phonological awareness (Bradley & Bryant, 1983), verbal memory (Byrne & Shea, 1979), or executive functioning (e.g., Bull & Scerif, 2001; Everatt, Warner, Miles, & Thomson, 1997; Sikora, Haley, Edwards, & Bulter, 2002; van der Sluis, de Jong, & van der Leij, 2004; Willcutt et al., 2001) or a double deficit in rapid naming and phonological awareness (Wolf & Bowers, 2000).

The present study focuses on a key theory of DD, the cerebellum deficit hypothesis (Nicolson, Fawcett, & Dean, 2001), or in its present form, specific procedural learning difficulties (Nicolson & Fawcett, 2007), which is described in detail below.

Automaticity Deficit

The ability to decode and recognize words to achieve fluency and speed is one of the main difficulties of those children who are identified as having dyslexia. Acquisition of

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reading skills follows a distinct pattern of progression from slow and effortful, to automatic and precise reading. As part of this process, words come to be viewed as distinct units rather than assorted phonemes (Downing, 1979). However, studies show that children with DD do not complete this process and exhibit poor recognition skills even after continuous practice (Hogaboam & Perfetti, 1978). After achieving a similar level of precision, the reading rate remains slow (van der Leij & van Daal, 1999) in comparison to children without reading disabilities. In addition, children with DD exhibit heightened sensitivity to various indexes that make reading more difficult, including phonological complexity, word frequency, word length, and processing speed. The heightened sensitivity is especially apparent when two or more such indexes are combined (Seymour, 1986; van der Leij & van Daal, 1999). These results support the assumption that reading difficulties experienced by children with DD are rooted in an automaticity deficit, which precludes effortless reading.

Based on this assumption, researchers have investigated whether this is a general deficit or one that is specific to reading skills. According to Nicolson and Fawcett (1990, 1994, 1996), reading difficulties that are typical of DD stem from a dyslexic automaticity deficit. This refers to a general condition that affects basic pronunciation skills, hearing, and processing of eye movements throughout development, and is ultimately expressed in reading difficulties (Nicolson et al., 1999; Nicolson, Fawcett, & Dean, 1995, 2001). According to this theory, deficits are inherently caused by poor cerebellum functioning, which plays a central role in skill learning and automaticity. Specific procedural learning difficulties, the current form of Nicolson and Fawcett's (2007, 2011) theoretical framework, is no longer limited to the cerebellum, but has been expanded to include all areas of the brain associated with procedural learning (e.g., prefrontal cortex surrounding Broca's area, parietal cortex, basal ganglia, and cerebellum).

Nicolson and Fawcett's theory is based on a study in which a dual-assignment paradigm was employed. Children were instructed to complete a primary motor task (such as balancing), while simultaneously performing a second task (such as counting backward). Results show significant deficits in the dual-assignment task among children with DD, whereas normal performance was reported for a single task. This may indicate that individuals with DD did not reach automaticity in the primary task, thus performance was impaired when they were required to focus attention on an additional task (Nicolson & Fawcett, 1990).

Nicolson and Fawcett's results have received a great deal of criticism. For one, they did not assess attention deficits or motor difficulties. When these variables were included, researchers were unable to replicate the results (Wimmer, Mayringer, & Landerl, 1998; Wimmer, Mayringer, & Raberger, 1999). These studies found that distinctions between children with or without DD were limited to phonological and naming tasks. In addition, Nicolson and Fawcett's task included counting backward, a task associated with known dyslexic deficits such as naming, phonological processing, and working memory, therefore performance in the dual-assignment task may actually have been indicative of standard dyslexic impairments rather than an automaticity deficit. Indeed, integrating responses to two different tasks may reveal difficulty in allocation of resources or other central processes, and not impaired motor learning automaticity (Savage, 2004). Moreover, Nicolson and Fawcett chose to measure skills acquired in natural settings and not under laboratory conditions, thus limiting the possibility of reaching conclusions regarding the process of skill learning. In an attempt to study the role of sensorimotor impairments in children with dyslexia, White et al. (2006) administered a wide range of tests that measured visual, auditory and motor skills as well as reading and phonological abilities. Their results showed that the most pronounced difficulty among children with dyslexia was related to their phonological abilities and not to their sensorimotor abilities. They nevertheless pointed out that though there are children with dyslexia who displayed impaired sensorimotor abilities, these deficits did not account for the reading difficulties that they experienced. Irannejad and Savage (2012) compared children with dyslexia to two control groups, one matched by reading age and the other by chronological age. They tested performance on various motor and cerebellar tasks and studied cognitive and reading measures. Contrary to Nicolson and Fawcett's theory, Irannejad and Savage found that performance in the motor and cerebellar tasks did not differ between the groups, whereas performance in the phonological task did differ between them.

An additional method of assessing the quality of procedural learning is by directly testing the quality and speed of skill learning. A series of studies (Vicari et al., 2005; Vicari, Marrota, Menghini, Molinari, & Petrosini, 2003) investigated implicit skill-learning among children with DD in laboratory settings using procedural learning tasks such as the Mirror Drawing (MD) task and the Serial Reaction Time (SRT) task. The advantage in using these tasks as measures for procedural learning in DD is that they do not include verbal elements. Furthermore, it is possible to attend specifically to learning speed while disregarding the motor speed variable. The task is therefore not influenced by phonological difficulties which characterize DD, or by comorbidity with motor difficulties. Results reported by Vicari et al. (2003, 2005) indicate that following numerous repetitions of the motor sequence, children with DD displayed a negligent decrease in reaction time, and insignificant differences in performance between familiar and random series. In the MD task, performance speed did not improve among children with DD. Vicari et al. (2003, 2005) concluded that children with DD exhibit a general deficit in learning skills that is not specific to verbal skills. These results are supported by numerous studies that indicate a deficit in sequence learning among individuals with DD (Howard, Howard, Japikise, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Stoodley, Harrison, & Stein, 2006).

Contrary to the above, various other studies did not find differences in SRT performance between the two groups (Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006; Waber et al., 2003). The inconsistent results cannot be attributed to task variance, as Waber et al. and Vicari et al. used similar tasks, whereas Kelly et al. used a more complex task. Furthermore, the inconsistencies cannot be attributed to population differences, as studies conducted on similar populations yielded contradicting results (population of college students: Howard et al., 2006; Kelly et al., 2002; Vicari et al., 2003; children aged 7–12 years: Vicari et al., 2005; Waber et al., 2003). Orban, Lungu, and Doyon (2008) suggest that the above studies place an emphasis on incidental learning in the fast acquisition phase rather than assessing further stages of skill learning, thereby limiting the validity of their results. Moreover, Nicolson and Fawcett (2011) explain that among a very large number of individuals with DD, the performance deficit is rooted in language procedural impairments. This impairment is linked to motor procedural abilities among certain individuals, which may explain the inconsistent results.

Studies that investigated automaticity in individuals with DD present several methodological issues that must be addressed. Studies conducted by Vicari et al. (2003; as well as Kelly et al., 2002, and Waber et al., 2003) compared a group of children diagnosed with DD with a group of children without DD but did not distinguish between the various levels of ability within the DD group. As a result, various characteristics of the DD population were not delineated, nor were associations between individual variables and SRT performance assessed. Furthermore, both tasks used in Vicari's research do not require high levels of processing skills, which makes it difficult to deduce the ranges of implicit learning skills (Poldrack & Gabrieli, 2001). Indeed, in a study that used the Spatial Contextual Cuing task that is considered a higher level of set learning than the SRT and MD, individuals with DD exhibited improved spatial set learning compared to individuals without reading disabilities (Howard et al., 2006), which contradicts the theory of a general deficit in DD.

As noted above, inconsistent findings have been reported in literature pertaining to the degree of specificity of skill acquisition deficits in the DD population. A possible explanation for this inconsistency may be a lack of attention addressed to specific verbal deficits within the DD group. Therefore, the current study attempts to investigate associations between specific verbal deficits (e.g., phonological and orthographic) and between various aspects of the skill acquisition process (both motor-perceptual and cognitive) within the general DD group.

Furthermore, as previous research failed to assess a range of skills, the current study tested learning skills using two tasks, the SRT and the Tower of Hanoi Puzzle (TOHP), which are two frequently used tasks that represent distinct forms of skill learning. The SRT assesses sequence learning skills (Ferraro, Balota, & Connor, 1993; Jackson, Jackson, Harrison, Henderson, & Kennard, 1995; Knopman & Nissen, 1987), whereas the TOHP tests cognitive learning skills (Cohen, Eichenbaum, Deacedo, & Corkin, 1985; Vakil, Shelef-Reshef, & Levy-Shiff, 1997). By using both types of tasks, reading deficits can be specifically associated with one of the two skills. In addition to employing two types of skill learning, numerous measures (e.g., baseline, learning rate, performance speed) were evaluated for a more specific analysis. Moreover, previous research that assessed DD and executive functions was unable to reach definitive conclusions (Howard et al., 2006; Kelly et al., 2002; Vicari et al., 2003; Vicari et al., 2005; Waber et al., 2003). The current research attempted to increase the conclusiveness of executive skill assessment through numerous repetitions of executive tasks. Consistent with the theoretical framework of specific procedural learning difficulties by Nicolson and Fawcett (2007, 2011), we hypothesized that individuals with DD would exhibit decreased skill-learning abilities as reflected by a more moderate learning rate, in comparison to individuals without DD. Furthermore, we predicted that measures of procedural learning rates would be associated with reading measures among individuals with DD.

Method

Participants

The current study includes 53 participants, 11 to 13 years of age, all sixth or seventh grade students. The control group consists of 30 children (12 boys and 18 girls) who did not report any reading difficulties, neurological impairments, or behavior issues and achieved average or above-average scores on a test battery.

The experimental group consists of 23 children (12 boys and 11 girls) who were diagnosed with reading disabilities and referred to the Nitzan Center in Petach Tikva, a city located in central Israel, because of varying levels of difficulty in school. Nitzan is the Israeli Association for Children and Adults with Learning Disabilities. All participants in this group exhibited gaps between their abilities and their scholastic achievements. As a result, their parents, teachers, or guidance counselors referred them for testing. None of these children had been previously diagnosed, nor had they been identified as having below-average intelligence. All attend public schools in Petach Tikva and are native Hebrew speakers. Their SES is varied, and they represent the full gamut of socioeconomic statuses in Israeli society. None of the children in the study have additional developmental, sensory, or motor issues. Some of the children were referred for additional testing for attentional issues such as attention deficit disorder (ADD) or attention deficit/hyperactivity disorder (ADHD) following this evaluation/diagnosis. These participants were excluded from the study as the research focused on reading disabilities and dyslexia. Children with an earlier diagnosis of ADD or ADHD are not referred for DD evaluations at this late stage. They tend to be evaluated earlier in their academic career.

A standard diagnostic assessment test was used, and the children diagnosed with DD were those who achieved low reading speed scores in the *Alef Ad Taf* (A to Z) battery, which includes several subtests (see below) that tap the various aspects of reading in Hebrew (A to Z; Shany, Lachman, Shalem, Bahat, & Zeiger, 2006). Intelligence was evaluated using two main tools, the *Test of Nonverbal Intelligence* (TONI; Brown, Sherbenou, & Johnsen, 1997) and the MAN tests of verbal intelligence, a norm-referenced test designed to evaluate verbal abilities in nine cognitive subskills (in Hebrew; Glanz, 2010). Only children who scored at least 80 on the TONI test were included. There were no significant differences in the intelligence scores achieved by the group with DD (M = 110.38, SD = 15.891) compared to the group without DD (M = 114.68, SD = 16.378), as measured with the TONI, $t(49) = 0.945$, $p > .05$. Participants were matched according to verbal fluency using phonemic and semantic fluency tasks (Hebrew version; Kavé, 2005). Only children who spoke Hebrew as their mother tongue and either were born in Israel or immigrated to Israel before the age of 6 were included in the study. Note that we believe the information provided above meets the minimum standards requested by the CLD Research Committee for the definition of specific learning disabilities (Rosenberg et al., 1993).

Written parental consent was obtained from all participants for a protocol approved by the university institutional review board. The research was also approved by the chief scientist of the Ministry of Education. Parents were informed that the research deals with learning processes in children with learning disabilities and received detailed explanations of the tasks that the children were to complete. The children were informed that they could stop participating in the study at any phase, without any ramifications. Every child completed a test battery, thus forming a profile of his or her learning abilities.

Reading Tests

Alef Ad Taf. The *Alef Ad Taf* (A to Z; Shany et al., 2006) is a test battery with national norms available in Hebrew that assesses reading, verbal memory, and linguistic skills. Of the extensive test battery, the following subtests are relevant to the current study:

Pseudo-Word Rate. This subtest measures decoding abilities. It comprises 33 nonwords, some of which include phonological structures that exist in the Hebrew language, and some of which do not.

Phonemic Segmentation. Used to measure phonological awareness, this subtest investigates the ability to break down words into phonemes using 8 nouns with three to nine phonemes.

Phoneme Deletion. This subtest is an additional measure of phonological awareness in which the ability to segment phonemes is assessed. Children are requested to pronounce various words while leaving out specific phonemes.

Number Naming (RAN Numbers). This subtest provides a measure of processing speed (rapid automatized naming; RAN). Children are requested to name digits as quickly as possible from a printed list of 50 digits.

Letter Naming (RAN Letters). This subtest provides a measure of processing speed (RAN). Children are requested to name letters as quickly as possible from a printed list of 50 letters.

Verbal Fluency. This subtest is a reflection of verbal memory. Children are requested to list as many words as they can, beginning with a given letter, within 30 s.

Skill Learning Tasks

SRT. The study was constructed using SuperLab (Cedrus, Inc.) software on a 15.4-inch-screen portable computer. Four white squares (3.3 × 3.3 cm) were presented horizontally at the center of the screen, on a grey background. At each stage, one of the squares was colored red and the participants were instructed to press the number on the keyboard from 1 to 4 that corresponds to the position of the red square. The red square appeared in a repeated sequence of 12 positions (121342314324). A learning block consisted of nine repetitions of the series of 12 positions, yielding 108 key presses. Participants completed seven blocks with a 45-s interval between blocks. In each block, the sequence of 12 positions began from a different position within the sequence to avoid explicit memory of the series. The subsequent stimulus appeared 300 thousandths of a second following a response, regardless of its accuracy. Reaction time was defined as the time that elapsed from stimulus' appearance until key press. Reaction time and accuracy of response were automatically recorded for analysis. After completing six learning blocks, participants were presented with a block containing a random sequence of 108 key presses. The participants were not given any indication of differences between the blocks, nor of the existence of a sequence.

Generate Test. This task was designed to assess explicit learning of the repeated sequence. After the random seventh block, participants were asked whether they perceived a sequence. Regardless of their response, they were informed of the existence of a repeated sequence and were asked to re-create portions of it. The sequence was then presented to them twice on the computer screen, and their task was to predict the subsequent position of the red square, by pressing the appropriate key. Thus, the maximum score is 24. Following every response, regardless of its accuracy, a red square appeared in the correct position. Participants were informed that reaction time was not important in this case, only precision.

TOHP. A computerized version of the task was used. Three pegs, numbered 1 to 3, appeared on the screen. On the far-left peg (1), four disks were arranged according to size, with the largest disk at the bottom. Participants were told that the goal was to move the disks from the far-left peg (1) to the far-right peg (3) in a minimum number of moves and as fast as possible, in keeping with the following rules: Only one disk at a time could be moved, no disk could be placed on a smaller one, and the middle peg had to be used. The optimal solution for four disks requires 15 moves. The computer automatically measures the time and the number of moves required to solve the puzzle.

Participants received a detailed explanation regarding the task, completed a short demonstration, and then worked independently in front of the computer for six trials. Once the participants solved a puzzle, they pressed "enter" to move on to the next one.

Results

The results are reported in two sections. The first section compares performance between the two groups (i.e., children with and without DD) on skill learning tasks. In the second section, associations between measures of reading and skill learning were tested. Performance on skill learning tasks was correlated (separately for each group) with various reading measures to elucidate whether particular aspects of reading are associated with particular aspects of skill learning.

Group Comparison

SRT. As in previous studies (Nissen & Bullemer, 1987; Vakil et al., 2001), the median reaction time (RT) was calculated for every series of 12 items, forming 9 medians for each block. The mean of medians for every block were analyzed (see Figure 1).

To analyze the learning rate as measured by RT, a repeated measures design was used, in a construct of 2 (group: individuals with or without DD) by 6 (learning: blocks 1–6). A main effect for learning was found, as RT significantly decreased throughout Blocks 1 to 6, $F(5, 250) = 47.732$, $p < .001$, thus exhibiting improved performance as a result of training. Furthermore, a main effect for group was found, as the RT of individuals with DD was higher than that of controls, $F(1, 50) = 15.825$, $p < .001$. An interaction effect was not found between the group and the influence of training, $F(5, 250) = 0.592$, $p > .05$, as no significant difference was identified in learning rates between individuals with or without DD.

To assess learning as expressed by the difference between the RT to the random sequence in comparison to the repeated sequence, a repeated measured design was used in a construct of 2 (group: individuals with or without DD) by 2 (learning: blocks 6,7). A main effect was found for learning, as RT increased between Blocks 6 and 7, $F(1, 50) = 64.416$, $p < .001$. A main effect for group was found, as RT of individuals with DD was higher than that of the control group for both measures, $F(1, 5) = 12.01$, $p < .01$. In this case as well, an interaction effect was not found between the group and the influence of training, $F(1, 50) = 0.432$, $p > .05$, as no significant difference was identified between individuals with or without DD in the increase in RT to the random sequence.

No significant differences were found between groups with DD ($M = 13.21$, $SD = 6.108$) and without DD ($M = 15.19$, $SD = 5.250$) in explicit learning of the repeated sequence, $t(48) = 1.201$, $p > .05$.

TOHP. For data assessment purposes, four scores were calculated for each attempt to solve the puzzle: number of moves to solution (minimum of 15 moves), total time to solution, time to first move, and time per move in each trial (total time divided by the number of moves to solution). Each one of these measures reflects a different aspect of the learning process, and thus a trade-off between speed and accuracy could occur: number of moves demonstrates accuracy, total time reflects solution speed, time per move corrects total time using number of moves, and time for first move reflects planning time. Learning is achieved when improvement is exhibited for both speed and accuracy.

To investigate the learning rate, a repeated measures design was used, in a construct of 2 (group: individuals with or without DD) by 6 (learning: Trials 1–6). For the dependent variable of number of moves to solution, a main effect for learning was found, indicating a significant decrease in number of moves from Trials 1 to 6, $F(5, 250) = 8.401$, $p < .001$. A main effect for group was not found, as the number of moves was similar in both groups, $F(1, 50) = 0.015$, $p > .05$. Interaction was therefore not found, as no significant difference was identified between individuals with or without DD in the rate at which the number of moves to a solution decreased, $F(5, 250) = 0.361$, $p > .05$ (see Figure 2).

For the dependent variable of total time, a main effect for learning was found, indicating a significant decrease in general RT as training progressed (Trials 1–6), $F(5, 250) = 34.918$, $p < .001$. A main effect for the group was not found,

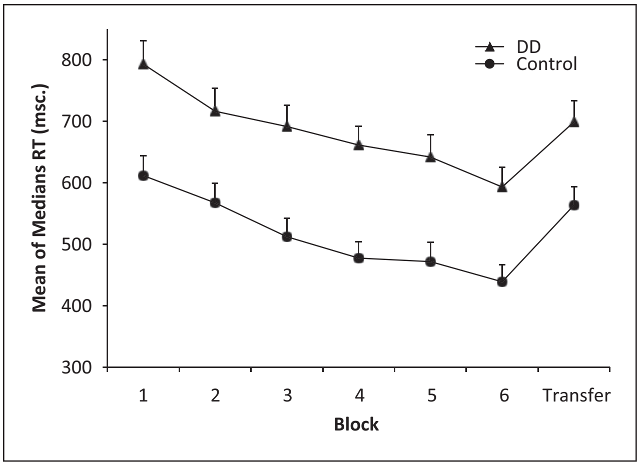

Figure 1. Performance of the groups with and without developmental dyslexia (DD) on the Serial Reaction Time task.

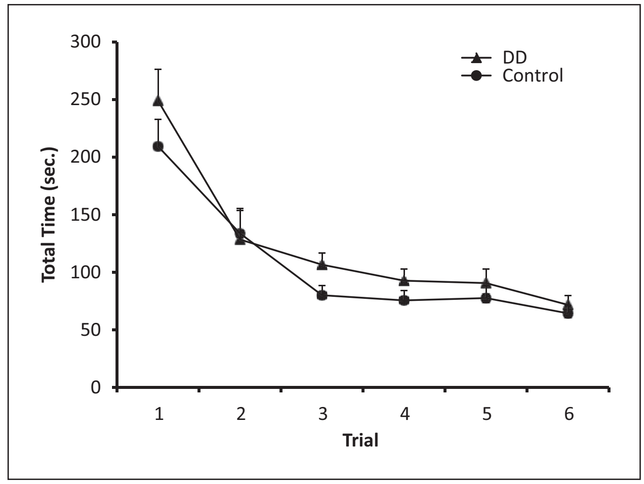

Figure 3. Performance of the groups with and without developmental dyslexia (DD) on the Tower of Hanoi Puzzle task, as measured by the total time to solution.

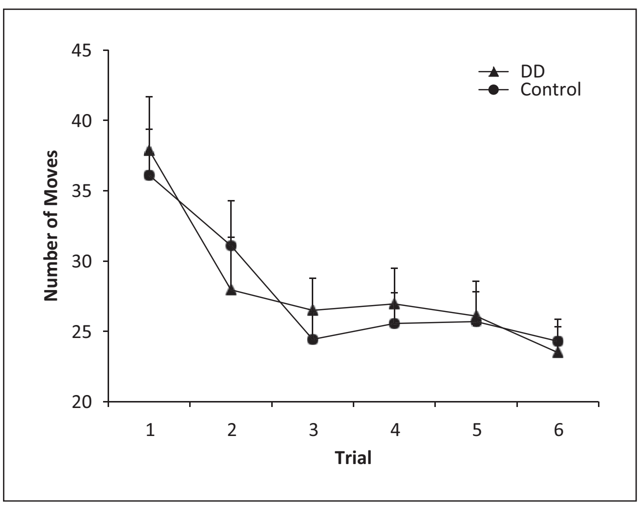

Figure 2. Performance of the groups with and without developmental dyslexia (DD) on the Tower of Hanoi Puzzle task, as measured by the number of moves to solution.

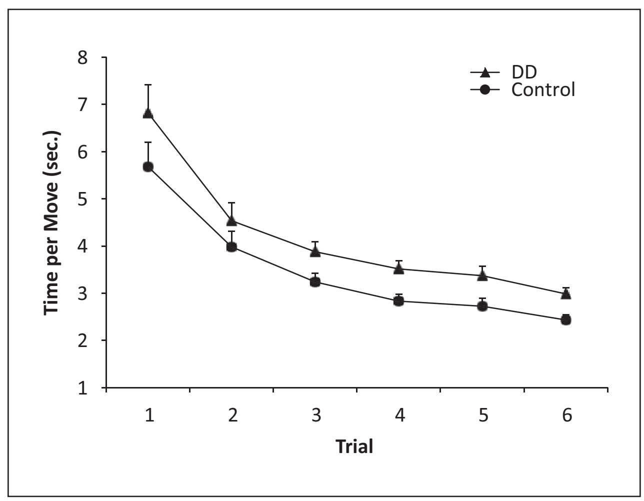

Figure 4. Performance of the groups with and without developmental dyslexia (DD) on the Tower of Hanoi Puzzle task, as measured by the average time per move.

as no significant difference was identified between individuals with or without DD in general RT per trial, $F(1, 50) = 1.531$, $p > .05$. Interaction was therefore not found in this case either, as no significant difference between individuals with or without DD was identified in the decrease rate of general RT, $F(1, 250) = 0.590$, $p > .05$ (see Figure 3).

For the dependent variable of time per move, a main effect for learning was found, $F(5, 250) = 59.835$, $p < .001$, indicating a significant decrease in time per move from Trials 1 to 6. A main effect for the groups was found as well, $F(1, 50) = 5.389$, $p < .05$, as time per move was higher for individuals with DD than individuals without DD. An interaction effect was not found between group and learning, $F(5, 250) = 0.432$, $p > .05$, as no significant difference between individuals with or without DD was identified in the rate at which time per move decreased (see Figure 4).

For the dependent variable of time for first move, a main effect for learning was found, $F(5, 250) = 23.604$, $p < .001$, indicating a significant decrease in time for first move from Trials 1 to 6. Group main effect did not reach significance, $F(1, 50) = 1.251$, $p > .05$, as no significant difference was identified between individuals with or without DD in time for first move. The learning by group interaction reached significance, $F(5, 250) = 4.260$, $p < .005$. As can be seen in Figure 5, the decrease in time for first move was more pronounced for the group with DD than for the control group.

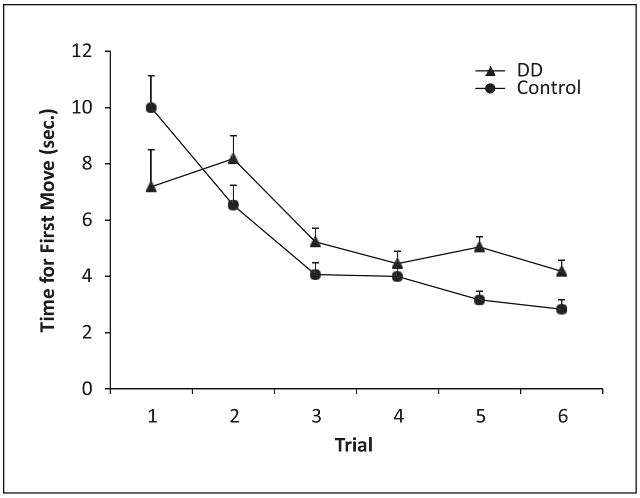

Figure 5. Performance of the groups with and without developmental dyslexia (DD) on the Tower of Hanoi Puzzle task, as measured by the average time for the first move.

Associations Between Reading and Skill Learning Measures

SRT. Pearson product–moment correlations were calculated between learning measures of the SRT and reading test scores for individuals with DD. Learning measures of the SRT include two scores: the difference between median RT in the first and sixth blocks, which reflects learning throughout the six blocks, and the difference in the mean values for the seventh and sixth blocks, as a measure of implicit sequence learning. Significant correlations were found only in the DD group, as correlations with the control group were scarce and inconsequential.

As shown in Table 1, the difference between Blocks 1 and 6 was significantly correlated with reading errors, pseudo-word rate, and number naming. The difference between Blocks 7 and 6 was significantly correlated with phoneme deletion and verbal fluency.

TOHP. Pearson product–moment correlations were calculated between learning measures of the TOHP and reading test scores for individuals with DD. Four scores were calculated for this purpose: the difference between general RT in the first and sixth trials, mean RT per move, number of moves, and time to first move. In this case as well, significant correlations were found only in the DD group, whereas correlations with the control group were scarce and inconsequential.

As shown in Table 1, time per move did not significantly correlate with any of the reading measures. Number of moves significantly correlated with reading speed (words per minute; WPM), silent reading, pseudo-word rate, and phoneme deletion. Time for first move significantly correlated with phonemic segmentation. Total time significantly correlated with letter naming.

To investigate the existence of differences between groups in terms of executive abilities, independent sample t tests were conducted for measures of the first trial of the TOHP. These measures represent pure executive abilities, as at this phase learning has not yet occurred. Differences were not found between groups for all measures of the first trial: number of moves, $t(50) = 0.351$, $p > .05$; general RT, $t(50) = 1.102$, $p > .05$; time per move, $t(50) = 1.439$, $p > .05$; and time for first move, $t(50) = 1.628$, $p > .05$. Thus, individuals with DD and without DD exhibited similar executive abilities.

Discussion

DD is a condition characterized by difficulties in reading skills. Various theories have been offered in an attempt to shed light on this prevalent disability. One prominent existing theory is the theory of specific procedural learning difficulties (Nicolson & Fawcett, 2007). According to this framework, difficulties are initiated via a wide-range deficit in brain mechanisms associated with procedural learning and automaticity, which affect general functioning in addition to reading skills. Numerous studies have been conducted regarding this theory; however, they present methodological issues. Most important, a range of skills was not assessed, nor were specific aspects of learning delineated and compared. The overarching goal of the current research is to assess whether the automaticity deficit in DD is a general disorder, or one specific to reading skills. In addition, previous methodological issues are resolved through use of various skill-learning tasks. An attempt was made to investigate skill automaticity, as exhibited in two tasks that represent different distinct forms of skill learning. The SRT assesses sequence learning skills whereas the TOHP tests cognitive learning skills.

Furthermore, various measures that reflect different aspects of the learning process were extracted from each task. SRT learning measures include two scores: one for general learning across the learning blocks, and the second for implicit sequence learning (transfer). Recent studies suggest using both measures when special populations are investigated to gain an in-depth understanding of the mechanisms involved (Nemeth et al., 2010; Nemeth & Janacsek, 2011). Four measures were generated from the TOHP: number of moves demonstrates accuracy, total time reflects speed, time per move reflects the overall time corrected by number of moves, and time for first move reflects planning time.

Consistent with the theoretical framework of specific procedural learning difficulties by Nicolson and Fawcett (2007, 2011), we hypothesized that individuals with DD

Table 1. Pearson Product–Moment Correlations Between Learning Measures of the SRT and TOHP and Reading Test Scores for Individuals With DD.

	SRT 1–6	SRT 7–6	TOHP TPM	TOHP NM	TOHP TFM	TOHP TT
Silent reading speed	.006	.008	–.219	.554*	–.353	.331
Reading errors	–.901*	.10	.236	.630	–.066	.723
Pseudo-word rate	.486*	–.401	–.268	.425*	–.022	–.014
Phonemic segmentation	–.411	–.354	–.358	.168	–.431*	–.037
Phoneme deletion	–.212	.703*	.226	–.858*	.068	–.447
Number naming RAN	–.508*	.231	.142	–.425	–.091	–.144
Letter naming RAN	.131	–.257	.269	–.105	.287	.465*
Verbal fluency	.647**	.631**	–.006	–.149	.062	–.270

Note. DD = developmental dyslexia; NM = number of moves; RAN = rapid automatized naming; SRT = Serial Reaction Time; SRT 1–6 = SRT learning; SRT 7–6: SRT transfer; TFM = time for first move; TOHP = Tower of Hanoi Puzzle; TPM = time per move; TT = total time.
*p < .05. **p < .01.

would exhibit decreased skill-learning abilities in comparison to individuals without DD. When comparing the two groups, the learning rate did not differ in either task, which is inconsistent with Nicolson and Fawcett's theory. However, results for both tasks consistently indicated slower performance among individuals with DD. These results are consistent with existing evidence of prolonged RT exhibited by those suffering from DD, which may indicate a deficit in information processing speed (Savage, 2004).

Furthermore, associations between reading measures and learning measures of the SRT and TOHP were identified predominantly among the DD population. Correlations were found between various measures of reading skills and skill learning. In the SRT, the difference between the first and sixth blocks indicated that learning correlated with measures of reading (pseudo-words, reading errors) and verbal processing rate (number naming). In addition, implicit set learning, as expressed by the difference in performance between the sixth and seventh block, correlated with measures of phonological awareness (phoneme deletion) and verbal memory (verbal fluency).

In the TOHP, learning was measured by a number of variables. Learning as measured by the number of moves was correlated with phonological abilities (reading speed [WPM], silent reading, pseudo-word rate, and phoneme deletion). Learning as measured by the time to the first move was correlated with phonological abilities (phonemic segmentation). Learning as measured by general RT was correlated with verbal processing speed (letter naming).

Our results may be understood in light of the double-deficit hypothesis, a prominent theory in DD research. According to this theory, DD is caused by two distinct deficits: RAN and phonological awareness. Although these two deficits may appear together, in most cases only the phonological awareness deficit is apparent. When both aspects appear jointly, the deficit is then considered particularly difficult (Wolf & Bowers, 2000). Keeping within this framework, performance in the SRT may be associated with rapid naming deficits that are typical of DD, and not with the phonological aspect of the disorder. The results of this research may indicate that when a child's reading deficit stems specifically from a rapid naming deficit instead of from phonological difficulties, skill learning will be more difficult.

Several of our hypotheses are related to the connection between reading assessments and learning, as expressed by the decrease in general RT, the mean time per move, and number of moves to solution after training. We hypothesized that test results that portray decreased reading levels would produce a more moderate learning rate. In the TOHP, correlations were identified between several of the reading and learning measures among individuals with DD. In contrast to the SRT, which was associated with rapid naming variables only, the TOHP correlated with phonological measures (e.g., segmentation of words and deletion of phonemes) as well. Therefore, it seems that this task can be associated with both aspects of DD. Accordingly, it may be predicted that increased difficulty in acquiring complex skills would result in an increased deficit in phonological abilities and rapid naming. Correlations between learning measures of the TOHP and auditory memory may also predict that the more difficulty experienced in learning the skill, the greater the deficits in auditory memory.

Additional correlations were identified between learning measures applied in the TOHP and several reading measures among individuals without DD, but these were scarce. This indicates that an association exists between learning the TOHP and reading, a connection that is much stronger among individuals with DD. Yet it is unclear why some measures of phonological abilities and rapid naming were found to correlate with learning measures of the TOHP, whereas others were not. To fully ascertain the essence of the relationship, there is a need for additional research.

Beyond an automaticity assessment in the TOHP task, executive abilities in both groups were compared as well. This was achieved by comparing performance measures in the first trial when learning has not yet occurred; therefore the comparison can be considered a pure measure of executive abilities. Differences were not found between groups in any of the measures, implying that individuals with and without DD portrayed equal executive abilities. Literature regarding executive deficits in individuals with DD is inconsistent, as a number of studies have found impairments (e.g., Narhi, Rasanen, Metsapleto, & Ahonen, 1997), whereas others have not (Klorman et al., 1999; Narhi & Ahonen, 1995; Tant & Douglas, 1983). A closer look at research that identified executive impairments in individuals with DD reveals that most tasks were based on speed (such as the Stroop task and Trail Making B). In contrast, tasks based on planning and problem solving (such as Tower of London and TOHP) did not highlight differences between groups, as individuals with and without DD succeeded to a similar degree. It is therefore possible that the fact that individuals with DD did not succeed in specific tasks can be attributed to slow processing speed instead of executive deficits. Furthermore, different tasks may have tapped into different perspectives of executive abilities, which are not all equally impaired in individuals with DD.

This study has several limitations that should be noted. The first is that our sample of children with DD was not sufficiently large to enable dividing the group into subgroups with different impairment profiles, one of which would be impaired sensorimotor abilities. This distinction could have produced a different pattern of performance on the procedural learning tasks for each subgroup. Furthermore, a larger sample size could have enabled us to conduct regression analysis, which is the more appropriate statistical approach to addressing our questions, rather than correlation analysis.

The possible educational implications of these findings are that skill-learning tasks can possibly be used as part of a diagnostic battery for DD. Furthermore, the possibility of training individuals with DD on such tasks might eventually lead to improved automatization that in turn might become generalized and have a positive effect on learning skills. These possibilities need to be addressed in future research.

Our original research goal was to further elucidate an understanding of Nicolson and Fawcett's (2007) specific procedural learning difficulties theory. As such, the degree to which our results support this theory must be ascertained. On one hand, performance did not differ between the two groups for either of the procedural learning tasks, which contradicts the specific procedural learning difficulties theory. On the other hand, meaningful correlations between measures of the procedural tasks and reading measures were found only in the DD group, which may support specific procedural learning difficulties theory.

One way to reconcile this apparent contradiction is by rationalizing that although the learning rate was similar between groups, the cognitive processes at the basis of performance may be different. In the control group, correlations were not found between task performance and reading measures. Therefore, it seems that different cognitive processes govern each of the abilities. In contrast, the results in the DD group might suggest that performance in procedural tasks is mediated by the same cognitive processes involved in language processing. Thus, although behavioral performance of the two groups may seem similar, the cognitive processes at their base may differ. Further research using functional imaging such as fMRI should investigate whether performing procedural tasks involves different brain processes in children diagnosed with DD compared to those without DD. Moreover, further research must also assess whether the areas activated are involved in language processing.

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