

Dissociation between the procedural learning of letter names and motor sequences in developmental dyslexia [☆]

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ABSTRACT

Motor sequence learning has been studied extensively in Developmental dyslexia (DD). The purpose of the present research was to examine procedural learning of letter names and motor sequences in individuals with DD and control groups. Both groups completed the Serial Search Task which enabled the assessment of learning of letter names and motor sequences independently of each other. Control participants learned both the letter names as well as the motor sequence. In contrast, individuals with DD were impaired in learning of the letter names sequence and showed a reliable transfer of the motor sequence. Previous studies proved that motor sequence learning is impaired in DD. The present study demonstrated that this deficit is more pronounced when the task to be learned involves linguistic units. This result implies that the procedural learning system of language is more deficient than the motor procedural learning system in individuals with DD. The dissociation between motor and letter names sequence learning in those with DD also implies that the systems underlying these two tasks are separable.

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1. Introduction

Developmental dyslexia (DD) is defined as unexpected, specific, and persistent failure to acquire efficient reading skills despite conventional instruction, adequate intelligence, and socio-cultural opportunity (American Psychiatric Association, 1994). Individuals with DD may have difficulties in acquiring a variety of language skills such as reading, writing and spelling as well as reading sub-skills such as word identification and phonological decoding (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Several theories which attempt to unravel the main deficits underlying DD have been reported in the literature. Despite decades of intensive research the underlying biological and cognitive causes of this reading impairment are still under extensive debate (for a review, see Démonet, Taylor, & Chaix, 2004). The mainstream hypothesis, i.e., *The Phonological Deficit Hypothesis* (Snowling, 2000), implicates a deficit of direct access to, and manipulation of, phonemic language units retrieved from the long-term declarative memory. This theory has been supported by numerous studies which indicated a phonological

deficit in DD (for a review, see Vellutino et al., 2004). However, individuals with DD exhibit difficulties in auditory and visual processing (Farmer & Klein, 1995), as well as attention (Facoetti & Molteni, 2001), and sensori-motor deficits (Nicolson & Fawcett, 1994). *The Phonological Deficit Hypothesis* cannot account for these additional deficits which have been reported in many individuals with DD, and has been facing growing criticism. Nevertheless, the wide range of DD difficulties has led researchers to search for other more basic deficits than reading which may underlie DD (Hari & Renvall, 2001; Nicolson & Fawcett, 1990; Stein & Walsh, 1997).

One of the theories which conceptualize DD as a learning disorder is the *Cerebellum Deficit Hypothesis* (Nicolson, Fawcett, & Dean, 2001). According to this view, dyslexics fail to automate new cognitive and motor procedures. This deficit arises from dysfunction of the cerebellum, which is involved in the automatization of new skills. This theoretical framework has been recently modified to its current form, *Specific Procedural Learning Difficulties* (Nicolson & Fawcett, 2008; 2011) according to which DD arises specifically from impaired performance of the procedural learning system for language. This defect stems from damage to one of the brain areas related to this system (such as the prefrontal cortex around Broca's area, the parietal cortex and sub-cortical structures including the basal ganglia and the cerebellum). Nicolson and Fawcett (2011) indicate that a subgroup of DD may also have a deficit in the motor procedural learning system, yet in their opinion it is not a requirement for the

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diagnosis of DD. Empirical work supporting this account attempts to examine individuals with DD on a variety of procedural skills (for a review see Folia et al., 2008).

1.1. Procedural learning

One of the tasks used for studying procedural learning is the serial reaction time (SRT) task (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 indicated by 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). There is clear evidence of learning, irrespective of the participants' conscious awareness of the repeated sequence. This kind of sequential learning has therefore been referred to as implicit learning. (for reviews, see Berry & Dienes, 1993; Seger, 1994; Shanks & St John, 1994).

One of the main questions in the research literature on the SRT task is what exactly is being learned in this task? When a participant performs the task, it is not clear whether he learns the sequence of manual responses or the sequence of the stimulus positions or both. The motor view of implicit sequence learning suggests that implicit learning is based on motor learning. Research supporting this account demonstrates that implicit learning cannot occur without motor learning (Willingham, Nissen, & Bullemer, 1989; Ziessler, 1994). On the other hand, the perceptual account of sequence learning suggests that learning involves the acquisition of contingencies amongst perceptual stimuli (Dennis, Howard, & Howard, 2006; Vakil, Kahan, Huberman, & Osimani, 2000). Evidence supporting this view comes from observational studies which demonstrate that learning can occur by observing a pattern of finger movements (Heyes & Foster, 2002). Another similar question regarding the SRT task is whether implicit sequence learning consists of a single learning mechanism or multiple mechanisms for different kinds of input or tasks that involve partially different brain structures. Several studies point to the possible existence of multiple learning mechanisms, each one for a specific kind of input such as tones, speech like material, shapes etc. (Conway & Christiansen, 2006; Goschke, Friederici, Kotz, & Van Kampen, 2001).

1.2. Motor versus language procedural learning in DD

The SRT task has been studied extensively in DD in order to examine motor procedural learning (for review see Folia et al., 2008). Several studies have revealed impairment in sequence learning among adults with DD as measured by the SRT task (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006). Other studies have reported intact sequence learning among individuals with DD (Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006). A recent study explored both the acquisition and consolidation stages believed to be involved in skill learning in DD. This study revealed that individuals with DD have a deficit in general skill learning of the SRT task, while the transfer measure and consolidation processes remained intact (Gabay, Schiff, & Vakil, 2012). This inconsistency between studies can be attributed to differences in the experimental design, sampling, procedures being used, etc. Indeed, previous research on the SRT task indicated several parameters which can affect implicit learning, including the length of the sequence being used (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 above differ greatly in these parameters. This makes it difficult to compare their results directly and to reach a clear conclusion on the SRT in DD. Moreover, Nicolson and Fawcett (2011) suggest DD stems mainly from a deficit in the procedural learning system of language, while some DD individuals may also be impaired in the motor procedural learning system. This suggestion might help clarify why some studies have demonstrated deficit in motor sequence learning in DD, while other studies have not.

Contrary to the extensive research on motor procedural learning in DD, only a few studies have examined language procedural learning in this population. Several studies employed the Artificial Grammar Learning (AGL) task (Reber, 1967). In this task, participants are shown a set of letter strings that conform to an underlying rule. In the training phase the participants memorize the letter strings. In a subsequent test phase the participants are shown new letter strings and are asked to judge whether they are constructed according to the artificial grammar or whether they contain violations of the grammatical structure. Classification of the novel strings significantly above chance level is taken as an indication for learning the structure of the grammar. Research on AGL in DD revealed mixed results. Rüsseler et al. (2006) demonstrated that AGL is intact in adults with DD. Yet, Pavildou, Kelly and Williams (2010) found that children with DD failed to learn the underlying rule.

Although the studies cited above examined procedural learning of motor and language deficits in DD, only one study has tested these different deficits simultaneously in a single study (Rüsseler et al., 2006). In this study the same participants performed SRT and AGL tasks. However, direct comparison is difficult due to the differences between these two experimental paradigms. Furthermore, it is also possible that these tasks tap different processes. A direct comparison of motor and language procedural learning (using the same experimental paradigm) is therefore necessary in order to understand the nature of procedural learning difficulties in DD.

The current study aimed to examine language and motor procedural learning in DD. Using an identical experimental paradigm enabled examination of whether motor versus language procedural learning difficulties may occur in individuals with DD. To the best of our knowledge, so far no research has examined letter names sequence learning in individuals with DD. These objectives were achieved by examining the Serial Search Task (SST; Goschke et al., 2001) in DD and control groups. In this task, four letters are presented visually in each trial, followed by a single letter presented auditorily. Participants are asked to press one of four response keys to indicate the location of the auditory letter in the visual display. The arrangement of the visual letters is changed from trial to trial so that either the key-presses (response sequence condition) or the auditory letters (letter names sequence condition) follow a repeating pattern, while the other sequence is random. The task allows examining whether participants acquired knowledge about a sequence of events in the absence of a regular response sequence, and vice versa. For example, participants in the letter names sequence condition can learn to anticipate the next letter name (for instance, they may learn that A–C–B is followed by D), but they cannot predict the next response before the mapping display appears, because there is no regular response sequence. Previous experiments have shown that normal readers learn both letter names and response sequences (Goschke, 1998b). The present study aimed to elucidate whether individuals with DD can learn both kinds of sequences as compared to normal readers.

Nicolson and Fawcett's (2011) model characterizes the deficits normally found among the DD population as arising to a great

extent from impairments in the procedural learning system of language (which is related to language–cortico cerebellar areas) and to a lesser extent, from impairment in the motor procedural learning system (which is related to motor–cortico cerebellar areas). Consequently Nicolson and Fawcett suggested that impairment in language procedural tasks will be found among all individuals in DD populations, whereas impairments in motor sequence procedural learning will be detected only in some individuals in DD populations. Following Nicolson and Fawcett's hypothesis it was predicted that the deficit in procedural learning as measured by the SST task will be more pronounced in learning of the letter names sequence as compared to the motor sequence.

2. Method

2.1. Participants

Twenty-eight university and college students (14 in each group) were selected for 2 experimental groups: a group with DD (8 female, 6 male) and a control group (11 female, 3 male). DD participants were recruited by advertisements and by approaching them through learning disabilities centers in universities and colleges. The mean age was 25.64, ($S.D.=2.84$, 25.07), ($S.D.=3.75$), in the DD and control groups, respectively. All participants with DD had a well-documented history of DD which was assessed by an educational psychologist. All students were paid 30 NIS (~\$7.5) for participation in the experiment or received a course credit. All participants were native Hebrew speakers with no reported signs of sensory or neurological deficits/attention deficit hyperactive disorder (according to the American Psychiatric Association, 1994) and came from families with 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-SPM test, Raven, 1992) verbal working memory (as measured by the forward and backward Digit Span subtest from the Wechsler Adult Intelligence Scale (Wechsler, 1997), and rapid naming test (digits/letters). Rapid naming measures were taken from the only individually administered test battery with national norms available in Hebrew, "Alef Ad Taf" (Shany, Lachman, Shalem, Bahat, & Zeiger, 2006). The digit naming speed subtest consisted of five digits: 1, 5, 9, 3, and 7, each repeated randomly 10 times. The 50 printed digits were presented to the participant, who had to read them aloud as fast as possible. The number of digits per minute was calculated. The letter naming subtest consisted of five (non-final) Hebrew letters: א (s), ב (a), ד (d), ג (g), and ל (l), each repeated randomly 10 times. The 50 printed letters were presented to the participant, who had to read them aloud, as fast as possible. The number of letters per minute was calculated.

The participants also completed a single word-reading tests and a non-word reading tests (Schiff & Kahta, 2009a, 2009b) in order to measure reading accuracy and speed abilities. Single word-reading tests were composed of 112 single words (for the accuracy measure subtest) or 104 single words (for the speed measure subtest). Non-word reading tests were composed of 45 non-words (for the accuracy measure subtest) or 114 non-words (for the speed measure subtest). In single word and non-word accuracy subtests the printed words were presented to the participant, who had to read them aloud as accurately as possible. The number of correct words read was calculated. In single word and non-word speed subtests, the printed words were presented to the participant, who had to read them aloud, as fast and as accurately as possible. Number of correct words read in 45 s was calculated.

The two groups did not differ in age or cognitive ability. However, as expected the performance of the DD group was worse than that of the control group in tests of single word and non-word reading as well as in rapid automatized naming tests and verbal working memory. The group with DD was comprised of 14 students at or below the 50th percentile in both the accuracy and the speed measures (see Table 1).

2.2. Materials and procedure

Stimulus presentation and the recording of response time and accuracy were controlled by a computer program (E-PRIME). Four Hebrew letters (א, ב, ג, ד) which are pronounced as *Alef*, *Bet*, *Gimel*, and *Daled*, respectively, recorded in a male voice, served as auditory stimuli. Auditory stimuli length was 250 ms. Response keys on the keyboard were from the second to the fifth keys from the left in the lower row of the keyboard.

The procedure followed that of Goschke et al. (2001). In each trial, four Hebrew letters (א, ב, ג, ד) were presented in a horizontal row on the screen. After a delay of 500 ms, one of the four letters was presented auditorily through headphones. The participants were told that they should press the key that corresponds to the position of the letter they hear through the headphones. After a

Table 1

Description for both control and DD group samples regarding cognitive and literacy scores.

Subtest	Group		
	Control	DD	<i>p</i>
Age (in years)	25.07 (3.75)	25.64 (2.84)	n.s.
Raven	56 (2.96)	54.37 (4.06)	n.s.
Digit span ^a (combined)	12.71 (3.07)	8.78 (1.805)	**
Letter naming	18.42 (2.62)	22.71 (3.53)	**
Digit naming	17.71 (1.77)	21.5 (3.43)	**
Word reading speed	87.142 (8.06)	61.28 (9.01)	**
Word reading acc	106.28 (2.84)	96.78 (4.83)	**
Non-word reading speed	52.57 (13.77)	26.14 (6.74)	**
Non-word reading acc	36.144 (7.409)	20 (5.18)	**

The values of word and non-word reading speed subtests represent the number of correct responses participants made in 45 s.

The values of word and non-word reading accuracy subtests represent the number of correct responses participants made (acc=accuracy).

** $p < .01$.

^a Standard scores, other raw scores.

response was made, there was a response-stimulus interval of 500 ms before the next trial was started. Participants performed a one-handed version of the SST task. In addition, all participants were instructed to perform the task using their dominant hand.

Each participant performed in a motor sequence condition and a letter names sequence condition. The order of the two conditions was counterbalanced across participants. Each condition began with a practice block of 80 trials. Each condition included three sequence blocks, each containing 160 trials (i.e., 20 repetitions of the eight-trial sequence), one random sequence block containing 80-trials, and a final sequence block containing an 80-trial block with 10 repetitions of the structured sequence. In the motor sequence condition, the repeating sequence was instantiated by the manual responses. In the letter names sequence, the repeating sequence was instantiated by the letter names. The order of the non-repeating dimension (letter names in the motor sequence condition and motor responses in the letter names sequence condition) was quasi-random. In block 4, the sequence of both responses and letter names was pseudo-random. Letter names and response sequences in block 4 were uncorrelated, and the unconditional probabilities of each letter name and each response were the same as in blocks with the repeating sequence.

The sequence used in the experiment was ambiguous in the following sense: (1) all first-order conditional probabilities were .5, that is, each sequence event had two different successors at different serial positions within the sequence. (2) The abstract structure of the repeating sequence was 13424312. This abstract structure was mapped in four randomly chosen ways for the four letter names or responses, yielding four different responses and four different letter names sequences initiating the same abstract sequence.

The four letters that were presented in the visual mapping in each trial followed a repeated sequence of either the motor responses or the letter names sequence. In the motor responses sequence condition, the responses (as well as the corresponding locations of the target letters in the mapping display) followed one of the eight-trial sequences, whereas the sequence of letter names was quasi-random. In the letter names sequence condition, the auditorily presented letters followed the eight-trial repeating sequence, whereas the response sequence was quasi-random. The sequences were presented immediately one after the other without any marking between them. The participants were given time to rest several minutes after every block. After each block the sequence began at a different serial position.

2.3. Explicit knowledge

Similarly to the work of Goschke et al. (2001), a sequence reproduction task was used to measure explicit knowledge. After completing the SST, the participants were informed of the existence of a repeating sequence (of either the motor or letter names according to the experimental condition they performed) and were asked to generate 30 trials reproducing the repeating sequence. In the motor sequence condition, the participants were asked to reproduce the sequence of motor responses as accurately as possible, using the same keys as in the SST. In the letter names sequence condition, the participants were asked to verbally reproduce the letter names sequence as accurately as possible. The verbally produced sequences were recorded by the experimenter. The participants were allowed to guess when they felt completely unable to recall parts of the training sequence.

3. Results

The groups (DD and control) were compared on different learning measures of the SST task: first is the *learning rate* across the three blocks of the repeated sequence. 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 is the *transfer* by comparing the repeated sequence (i.e., third block) and the random sequence (i.e., fourth block). Reaction times and accuracy rates were calculated for each measure. Explicit memory was measured by sequence reproduction task (Goschke et al., 2001).

3.1. SST accuracy

3.1.1. Learning rate—Blocks 1–3

The mean accuracy rate of the two groups in all first three blocks was submitted to a $2 \times 3 \times 2$ ANOVA with group (DD vs. controls) as a between-subjects factor and learning (1–3) and sequence type (letter names vs. motor) as within-subjects factors. There were no significant main effects or interactions (all $p > .14$).

3.1.2. Transfer—Block 3 vs. block 4

The mean accuracy rate of the two groups in the third and fourth blocks was submitted to a $2 \times 2 \times 2$ ANOVA with group (DD vs. controls) as a between-subjects factor and transfer (3 vs. 4) and sequence type (letter names vs. motor) as within-subjects factors. There was only a marginally significant group effect $F(1, 26)=4.09, p=.053$. Overall control participants were more accurate than the DD participants. There was no indication of a speed-accuracy tradeoff.

3.2. SST reaction time

Similar to Goschke et al., (2001) study, RTs below 200 ms or above 3000 ms were excluded from the analysis. Means of the remaining RTs for correct responses were computed for each participant and each block, separately for the letter names and motor sequence. Preliminary analysis revealed that the order in which the two sequences were conducted did not interact with the group variable. The results, therefore, were analyzed across sequence order. Fig. 1 presents the mean of RT as a function of blocks of the SST task for both groups.

3.2.1. Learning rate—Blocks 1–3

The mean of reaction times of the two groups in all first three blocks were submitted to a $2 \times 3 \times 2$ ANOVA with group (DD vs.

controls) as a between-subjects factor and learning (1–3) and sequence type (letter names vs. motor) as within-subjects factors. There was a main effect of group. Overall, the DD group was slower than the control group, $F(1, 26)=13.974, p < .01$. There was also a main effect for learning $F(2, 52)=9.58, p < .01$ as indicated by decrease in the RT across the three learning blocks. The sequence type main effect was not significant, $F(1, 26)=2.78, p=.107$. The group by learning interaction was marginally significant $F(2, 52)=2.84, p=.067$, indicating a trend toward difference in the learning curve between the two groups. The control group presented a steeper decline in RT between the repeated blocks compared to the DD group. The group by sequence type interaction was not significant, $F(1, 26)=1.83, p=.187$. The learning by sequence type was not significant, $F(2, 52)=1.43, p=.247$. Finally, the interaction of learning, sequence type, and group was not significant, $F < 1$.

3.2.2. Transfer—Block 3 vs. block 4

The critical test of whether the participants acquired specific knowledge about the sequences was in the comparison of the random block (4) and the immediately preceding structured block (3). The mean of reaction times of the two groups in the third and fourth blocks were submitted to a $2 \times 2 \times 2$ ANOVA with group (DD vs. controls) as a between-subjects factor and transfer (3 vs. 4) and sequence type (letter names vs. motor) as within-subjects factors. The DD group was slower overall as indicated by main effect for group $F(1, 26)=16.55, p < .01$. The main effect for sequence type was significant, $F(1, 26)=8.39, p < .01$, indicating that participants responded more quickly to the letter names sequence, as compared to the motor sequence. There was an overall increase in the RT to the random sequence (block 4) compared to the repeated sequence (block 3), $F(1, 26)=11.63, p < .01$. The group by sequence type interaction was far from significance, $F < 1$. The group by transfer interaction was marginally significant, $F(1, 26)=3.53, p=.07$. Importantly, there was a reliable interaction of transfer, sequence type, and group, $F(1, 26)=8.65, p < .01$. In order to analyze this interaction, separate 2 (transfer) $\times 2$ (group) ANOVAs were computed for each sequence type. For the motor sequence, the group by transfer interaction was far from significance $F < 1$, suggesting that both groups learned the specific motor sequence. In contrast, for the letter names sequence, the group by transfer interaction was significant, $F(1, 26)=7.89, p < .01$. Further analysis revealed that the control group showed significant increase in RT to the random block compared to the repeated block $F(1, 26)=14.909, p < .01$. In marked contrast, DD group did not show the same expected increase in RT to the random block compared to the

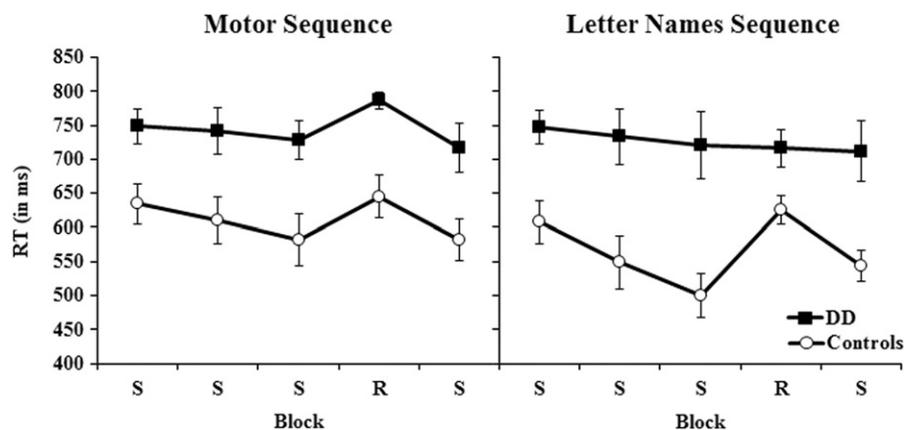


Fig. 1. Mean of RT of the DD and control groups in the motor and letter names sequences of the SST. Error bars represent standard errors.

repeated block $F < 1$, indicating no learning of the repeated letter names sequence. Subsequent analysis was conducted in order to determine if sequence learning impairment was related to general slowness of the DD group. An initial baseline performance measure (mean RT of the first sequence in the first block which was introduced to the participant) as well as transfer measure of the letter names sequence condition (subtracting average RT in the fourth block from average RT in the third block) was calculated for each participant. Pearson correlation revealed these two measures were not correlated in either the control ($r = .05$, $F < 1$) or the DD groups ($r = -.05$, $F < 1$), suggesting that DDs' general slowness was not responsible for their verbal sequence learning deficit. Finally, in order to examine fatigue/practice effects, the performance of the two groups was compared in the fifth and the third blocks. The triple interaction of group, sequence type and block did not reach significance ($p > .1$), suggesting fatigue/practice effects could not explain the current results.

3.3. Sequence reproduction task

The analysis followed that of Goschke et al. (2001). The number of correct chunks with 2–8 elements (chunks that were also contained in the training sequence in a non-overlapping manner) was first determined. A reproduction index was computed by determining the percentage of elements that were included in the correct chunks of three or more elements. A one-way ANOVA yielded no reliable group differences, $F < 1$. (Letter names sequence 48.7%, 36.1% for the control and DD groups, respectively, motor sequence 34.28%, 30.23%, for the control and DD groups, respectively).

4. Discussion

The present study examined letter names and motor sequence learning in participants with DD and control participants. Using the SST enabled investigation of the procedural learning of motor and letter names sequences independently of each other. The results indicate dissociation between letter names and motor sequence learning in individuals with DD. The control group did not differ in sequence learning of the letter names or the motor stimulus, whereas the DD group performance was dependent on the sequence that was learned in the task. Specifically, it was found that both groups showed transfer when spatial locations and manual responses followed a repeated sequence. In marked contrast, only controls showed a reliable transfer when the letter names sequences followed a repeated pattern, while the DD group failed to show this expected increase. These results indicate that individuals with DD have difficulty in the procedural learning of letter names sequences. This impairment may be largely a direct consequence of an underlying dysfunction of the procedural learning system of language.

Since the SST task is associated with language components, it might be argued that DDs' language problems might be responsible for their letter names sequence learning deficit. Similarly, DDs' slowness in processing language material might limit their ability to develop knowledge about the verbal repeating sequence. While these issues should be addressed by future studies, several indications in the current study are in contrast with those claims. First, although participants with DD may suffer from language deficits, they exhibit substantial difficulties in processing of non-linguistic information as well (Fawcett & Nicolson, 1994, 1995; Nicolson & Fawcett, 1994; Nicolson, 1994; Wolf, 1999). This general processing deficit might cause slowness whether visual-verbal associations (SST tasks) or visual-motor associations (SRT tasks) are being processed and result in

different initial baseline performance for DD and control groups. Yet, we believe that initial baseline performance and learning measures on procedural tasks (learning rate and transfer) are independent of each other. The latter are crucial measures of procedural learning, while the former reflects a basic initial performance on the task. Previous research on elderly populations provided empirical evidence for this independency on several procedural learning tasks, such as the serial reaction time task (Howard & Howard, 1989), Tower of Hanoi (Vakil & Agmon-Ashkenazi, 1997) and procedural reading tasks (Moscovitch, Winocur, & McLachlan, 1986). Namely, in spite overall slowness in reading time or reaction time, elderly participants exhibited the same amount of learning as control participants. A similar pattern of results was previously found in DD and control groups of participants which performed the SRT task (Gabay et al., 2012). Specifically it was found, that in spite of their overall slowness, DD participants were capable of learning the sequential properties of the SRT task on the same level as normal readers. Similarly, in the present study RT baseline and letter name sequence learning were not correlated for either the control or the DD groups, suggesting that DDs' general slowness in processing language material was not responsible for their verbal sequence learning deficit. Another indication in favor of language procedural learning deficit relates to the special properties of the SST task. Both the motor and letter names conditions of the SST task require processing of the same language stimuli. In both conditions participants listen to an auditory letter and locate it in a visual display by making a motor response. Language problems such as impaired language processing speed or difficulty in matching between verbal auditory letters to visual stimuli should affect both conditions in a similar manner, rather than affecting one condition while leaving the other untouched. At the same manner, if general slowness in processing verbal-visual associations harms the development of sequential knowledge, it should have similar influence on both conditions. Thus, it appears unlikely these claims can account for the learning deficit of the verbal name sequence in the DD group, since they showed entirely intact learning of motor sequence, even though average RTs were as high as for the verbal names sequence ($F < 1$).

To conclude, if language problems (such as impaired language processing speed or difficulty in matching between verbal auditory letters to visual stimuli) had influenced DDs' performance, both the motor and letter names conditions should be impaired in the DD group (since both require processing/matching of language material). Similarly, if unspecified procedural learning impairment had influenced DD results, both the motor and letter names conditions would be impaired in the DD group (since both require procedural learning ability). Rather, the dissociation between letter names and motor conditions in the DD group indicates a specified underlying dysfunction of the procedural learning system of language in DD.

4.1. Motor versus language procedural learning in DD

In accordance with previous research (Gabay et al., 2012; Rüsseler et al., 2006) the present study demonstrated that DD individuals can learn motor sequences. Regarding the letter names sequence, the present study is the first to report a deficit in letter names sequence learning among individuals with DD. When the sequence to be learned involves language units, individuals with DD might have difficulties in learning the sequence. Previous research also revealed that children with DD have difficulties in the procedural learning of letter strings (Pavlidou & Williams, 2010; Pavlidou et al., 2010). It was found that individuals with DD were impaired in learning an abstract rule as measured by the AGL task. The present results are in

accordance with Pavildou et al., since they demonstrate that the impairment of procedural learning in individuals with DD is specific to language related material. The present research also contributes to a large body of theoretical and empirical studies which point to a possible link between procedural learning and language (Christiansen, Conway, & Onnis, 2012; Conway & Christiansen, 2006; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011; Hedenius et al., 2011; Lum, Gelgic, & ContiRamsden, 2010; Lum, Conti-Ramsden, Page, & Ullman, 2011; Tomblin, Mainela-Arnold, & Zhang, 2007; Ullman et al., 1997; Ullman, 2001, 2004).

4.2. Developmental dyslexia—A deficit in the procedural system of language?

Several inferences can be drawn from the pattern of obtained results at the theoretical level. According to the *Phonological Deficit Hypothesis*, dyslexia stems from a deficit in phonological skills. It should be noted that it is still not clear what a phonological deficit means. Several researchers proposed that individuals with DD have deficient phonological representations (Swan & Goswami, 1997). Alternatively, Ramus & Szenkovits (2008) suggested that the nature of the phonological deficit in DD may arise from a deficit in access to phonological representations rather than a deficit in the phonological representations themselves. They proposed that the deficit may lie in short-term processes operating on phonological representations. In the SST task participants are required to locate an auditory presented target letter in a visual display. Both the letter names condition and the motor condition involve the processing of the same letter names units. The amount of training as well as the complexity and length of the sequences are identical. The only difference between these two conditions is the sequence being learned (whether the letter names versus motor responses follow a repeated pattern). Thus, the prediction of the phonological deficit hypothesis (as a representation deficit in DD) would be a deficit in both conditions, since both of them require processing of verbal material. The alternative account of DD as a problem of phonological access can explain DD difficulties in the letter names sequence condition which may require the involvement of short-term memory processes for verbal material. However, recent studies suggest that implicit learning processes might not be correlated to working memory capacities in both normal (Kaufman et al., 2010; Unsworth & Engle, 2005) and special populations (Lum et al., 2011). Thus, this explanation may seem less probable to explain the present results.

Another view of dyslexia, as a learning disorder, is the *Specific Procedural Learning Difficulties* (Nicolson & Fawcett, 2008; 2011). According to this account, DD stems mainly from a deficit in the procedural system of language. Accordingly, the defect of procedural learning in DD will be more pronounced in the letter names condition than in the motor condition. The present results suggest that the ability to gain knowledge about structured language patterns is impaired in individuals with DD and not just the ability to encode or process the letter names units. As indicated earlier, both conditions (motor versus letter names) require processing of language units, and the only difference between them was which sequence was introduced repeatedly. The present results, therefore, are primarily in accordance with the *Specific Procedural Learning Difficulties* account. They confirm the prediction that language aspects of procedural learning are the most impaired in DD.

It should be noted that a deficit in the procedural system of language may impact the ability to acquire skills related to language. Deficits in procedural learning of language may cause difficulties in acquisition of any skills or sub-skills related to language such as reading, writing, spelling as well as phonological decoding and word identification. All of these deficits were found among individuals with DD (for a review see Vellutino et al., 2004).

The special features of the SST task make it suitable for examining other possible explanations for the results. Several researchers have proposed that temporal processing (Howard et al., 2006) and spatial attention (Mayr, 1996) might be involved in the SRT task. These cognitive abilities also seem to be impaired in DD (Facoetti & Molteni, 2001; Farmer & Klein, 1995). For example, Howard et al. suggested that a deficit in temporal processing may account for the deficit of individuals with DD in SRT tasks. Nevertheless, difficulties in temporal processing or spatial attention might occur in both conditions in the SST task. Since dissociation is manifested in DD, these other accounts can be ruled out. In a similar vein, it could be argued that impaired letter names sequence learning in DD might result from unreported attentional problems in the DD group (DSM criteria was used in the present study in order to rule out possible contamination of ADHD problems in the DD sample). Even if the presence of attentional factors might play a role in participants' performance on sequential learning tasks, there is no reason to believe it would differentially affect the verbal names and motor sequence learning tasks.

The dissociation between motor and letter names sequence learning in those with DD also implies that the systems underlying these two tasks are not identical. The present results are also in accordance with the view that there are multiple mechanisms for different kinds of sequences or tasks that partially involve different brain structures. Previous research revealed Broca's aphasics have difficulties in learning the letter names sequence in the SST task, whereas learning of the motor sequence was intact. Wernicke's aphasics learned both sequences (Goschke et al., 2001). This research implies that the Broca area is one of the brain areas underlying letter names sequence learning. Since individuals with DD have a deficit in sequential learning of letter names, it may be suggested that this is due to impairment in the procedural system of language which includes the Broca area. This assumption was also suggested by Nicolson and Fawcett's (2011) refined model, and requires further anatomic research.

In conclusion, the present study suggests an empirical link between procedural learning and language. Individuals with DD show learning of spatio-motor sequences while the ability to learn letter names sequences is impaired. In conjunction with the SPLD framework, it is suggested that DD stems mainly from an underlying dysfunction of the procedural learning system of language.

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