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SHORT REPORT

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Procedural and declarative learning in dyslexia

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The procedural deficit hypothesis claims that impaired procedural learning is at least partly responsible for the deficits in learning to read seen in children with developmental dyslexia. This study used a reading ability-matched design to examine group differences in both procedural and declarative learning. Both children with dyslexia and typically developing children demonstrated procedural learning on a serial reaction time task, although learning in the typically developing group increased at a greater rate towards the end of the task compared with children with dyslexia. However, these results do not provide strong evidence for the procedural deficit hypothesis, because poorer procedural learning in the group with dyslexia may reflect impairments in motor learning, rather than sequence specific procedural learning. In addition, neither group showed a relationship between procedural learning and reading ability.

KEYWORDS

declarative learning, dyslexia, language, memory, procedural learning

1 | INTRODUCTION

Developmental dyslexia is a disorder characterized by impaired printed word recognition and spelling in spite of normal IQ and educational opportunities (Bishop & Snowling, 2004). It affects between 3% and 7% of the population (Barbiero et al., 2012; Snowling, 2013). Profiles of cognitive impairment in dyslexia show substantial heterogeneity (Peterson & Pennington, 2015), but deficits in phonological awareness and decoding are the most salient. The procedural deficit hypothesis claims that reading impairments seen in dyslexia are at least partly the result of deficits in a procedural memory system (Nicolson & Fawcett, 2007). This view is based on a dual process view of memory, which sees the procedural learning system as being involved in learning the statistical regularities and rules that govern language. By contrast, conscious declarative learning, which supports a mental lexicon of word-specific knowledge, is claimed to be unimpaired in dyslexia, possibly even compensating for procedural memory deficits over time (Ullman & Pullman, 2015). It has been claimed that procedural memory for sequential information may be particularly impaired in dyslexia (Nicolson & Fawcett, 2010).

This view has generated a substantial body of work, with inconsistent results to date (see Lum, Ullman, & Conti-Ramsden, 2013; Schmalz, Altoè, & Mulatti, 2016, for reviews). The vast majority of these studies have compared procedural learning (assessed using the serial reaction time task [SRT: Nissen & Bullemer, 1987], which compares the speed with that a participant responds to stimuli that follow a covert sequence to those that do not) in groups of children with dyslexia and age-matched control children.

2 | EXPERIMENTAL DESIGN

One criticism of studies of procedural learning in children with dyslexia is that none to date have included a control group matched for reading ability. Deficits in procedural learning in children with dyslexia compared with age-matched controls might conceivably be the product of differences in reading experience. One way to get around such an objection is to compare children with dyslexia with children matched for reading ability: any differences between such groups cannot reflect differences in reading skill and would therefore suggest that children with dyslexia suffer a fundamental deficit on the task assessed.

3 | DECLARATIVE MEMORY

Another limitation of previous studies is that measures of procedural learning have seldom been compared with measures of declarative learning. In normal learning, both procedural and declarative mechanisms are thought to operate together (Poldrack & Packard, 2003), working in competition to ensure learning is optimized (Foerde, Poldrack, & Knowlton, 2007). The few studies of procedural learning in children with dyslexia that have assessed declarative memory have confined themselves to measures of non-word repetition (Hedenius et al., 2013; Menghini, Finzi et al., 2010) and digit span (Deroost et al., 2010; Stoodley, Ray, Jack, & Stein, 2008). All report significantly poorer performance for dyslexic groups on both of these types of task, but performance on more comprehensive tests of verbal declarative memory alongside measures of procedural learning has not been assessed.

This study investigates whether impaired procedural learning is a potential cause of reading difficulties in dyslexia. If impaired procedural learning is a causal risk factor for dyslexia, then we should expect to see poorer procedural learning on a serial reaction time task in children with dyslexia compared with typically-developing children matched for reading ability.

The dyslexic sample was drawn from a group of children with a formal diagnosis of dyslexia attending specialist schools, whereas a comparison group was drawn from younger children in mainstream classrooms that had been recruited for a previous study. Procedural and declarative learning were assessed to enable us to examine group differences in both.

4 | METHOD

4.1 | Participants

Forty-eight children aged between 7 and 11 years took part in the study. There were 23 children with dyslexic difficulties (mean age = 117.04 months; *SD* = 13.77) and 25 typically developing reading ability-matched controls (mean age = 91.40 months; *SD* = 5.84). The dyslexic group was recruited from specialist schools for children with dyslexia in both Surrey and North London. Data from 25 children who had taken part in a previous study were used to form the reading age control group. The control group children were matched with the dyslexic group using raw scores on the TOWRE-2 sight word efficiency test (Torgesen, Wagner, & Rashotte, 1999). Ethical approval for the study was granted by the University College London research ethics committee.

4.2 | Measures and procedure

Children with dyslexia were tested individually in two 25-minute sessions 1 week apart. Tasks were completed in a fixed order.

4.3 | Reading tasks

4.3.1 | Test of word and non-word reading efficiency (TOWRE-2: Torgesen et al., 1999)

Children completed the sight word efficiency and phonemic decoding efficiency subtests from the TOWRE, where they were required to read aloud a list of words of increasing difficulty under timed conditions.

4.4 | Verbal declarative memory task

4.4.1 | Word Lists subtest from the Children's Memory Scale (Cohen, 1997)

This task required children to recall as many words as possible from a list of 10 spoken words irrespective of order. A learning score was derived from the total number of words correct on the first six attempts to recall this target list. Following the first presentation, only words omitted by the children were represented. Children were then presented with a distractor word list and asked to recall the target list again without representation. Scores on all lists were summed to form a learning score for each child. Recall of the target list was requested again at the end of the testing session (delayed recall score) and during a second testing session a week later (consolidation score).

4.5 | Procedural learning task

4.5.1 | Serial reaction time task (SRT: Nissen & Bullemer, 1987)

The traditional SRT task follows a deterministic structure, whereby the first four blocks of the task follow a predetermined covert sequence and the final (or penultimate) block is random. Although this is the version used in the majority of studies investigating the procedural deficit hypothesis, it has been criticized for not fully dissociating procedural and declarative learning (Shanks & Johnstone, 1999). More complex versions that use an alternating or probabilistic structure for the sequence throughout the task have been developed to combat this criticism.

We devised a probabilistic serial reaction time task based on Schvaneveldt and Gomez (1998) to investigate sequential procedural learning. It used a 12-item second-order conditional sequence (314324213412) for the locations in the task with a probability of 0.9 and an alternative sequence (431241321423) with a probability of 0.1 (for a discussion of second-order conditional sequences and implicit learning see Reed & Johnson, 1994). The task began with 10 practice trials with equal probabilities of each sequence and the subsequent recorded portion of the task included 10 blocks of 100 trials, divided into five epochs. Each block began with a randomly chosen bigram from the probable sequence and the subsequent locations in the block followed the sequential probabilities outlined above.

The task displayed four boxes arranged in a diamond pattern on the screen of a laptop computer, which was connected to an Xbox gamepad controller. On each trial, a yellow smiley face appeared in one of the four boxes. Children were asked to press the button that matched the position of the smiley face as fast as possible. Children were required to press the correct button before going on to the next trial. A short pause between successive blocks enabled the children to take short breaks if needed and the task was manually restarted as soon as the child was ready to continue. To motivate the child, at the end of each block, the task reported whether they had been faster or slower than in the previous block. The program recorded RTs and accuracy for each trial. The interval between trials was 250 ms and the task took 20–25 min to complete.

5 | RESULTS

Means, standard deviations, and reliabilities for all tasks by group are shown in Table 1. As expected, in spite of being matched for word reading fluency, the word and non-word reading standard scores of the dyslexic group were considerably lower than the age-matched typically developing group. The mean scores for the verbal declarative memory measures were higher for the dyslexic group than the control group, but the group and memory interaction in an ANOVA with group (2 levels) and declarative memory (3 levels) showed these differences were not significant: $F(1.14, 52.54) = .89$, $p = .36$, $\eta_p^2 = .02$.

5.1 | Procedural learning

The principal measure of procedural learning for serial reaction time tasks is the difference between response times for trials that follow a predictable sequence and those that do not. For the RT analyses in this task, only correct responses were included and outliers were removed using a moving criterion based on sample size (Selst & Jolicoeur,

TABLE 1 Means, standard deviations, and task reliabilities by group, with group differences, and effect sizes

	Typically developing group (n = 25)				Dyslexic group (n = 23)						
	Mean	*SD*	Min	Max	Mean	*SD*	Min	Max	*t*	*d*	Reliability
Age in months	91.40	5.84	85	105	117.67	13.81	93	138	−8.28	−2.46	-
Gender (f/m)	9/16	-	-	-	7/16	-	-	-			-
Handedness (r/l)	25/0	-	-	-	20/3	-	-	-			-
TOWRE-2											0.90
Words (raw)	49.84	7.49	32	60	48.96	16.04	20	76	0.24	0.07	
Words (standard)	107.20	5.16	99	118	88.83	9.65	65	105	8.13	2.40	
Non-words (raw)	28.64	8.76	16	50	22.13	10.58	5	48	2.31	0.67	
Non-words (standard)	112.04	8.75	96	132	91.83	9.14	73	113	7.81	2.26	
Word Lists											0.84
Learning	31.40	7.12	16	45	33.09	5.70	21	40	−0.91	−0.26	
Delay	5.80	2.06	1	9	6.09	1.78	3	9	−0.52	−0.15	
Consolidation	4.20	1.98	1	8	4.26	1.68	1	7	−0.12	−0.03	
SRT1 RT Difference	0.12	0.04	0.02	0.20	0.14	0.07	0.01	0.27	−0.76	−0.22	0.26–0.66[a]

[a]Higher reliability estimate obtained from pilot test with 46 adult participants; lower estimate from previous study with 7 year old children.

1994) to control for the unequal number of trials in the probable and improbable sequences. Baseline response speed was controlled by dividing children's procedural learning score by their overall speed of response, such that a positive score indicated procedural learning (improbable sequence RT – probable sequence RT)/([improbable sequence RT + probable sequence RT]/2). See A1 in appendix for the means and standard deviations for each group per epoch and sequence prior to this control.

As shown in Figure 1, there was evidence of procedural learning on the serial reaction time task in both groups, because RTs for the probable sequence were faster than for the improbable sequence across all blocks in both groups.

To investigate whether there was a difference between groups in the level of procedural learning on the serial reaction time task, an ANOVA was performed with group (2 levels: control group (TD) vs. dyslexic group (DD)) as a between participants factor, and sequence (2 levels: probable vs. improbable) and epoch (5 levels: epochs 1–5) as within participant factors. This method of analysis was selected to facilitate comparison with the results of previous studies of procedural learning in dyslexia.

A main effect of sequence type confirmed that RTs on probable sequences were significantly faster than on improbable sequences (F [1, 46] = 224.28, $p < .001$, $\eta_p^2 = .83$) (Probable sequence mean = 601.00 ms, SD = 121.38 ms; improbable sequence mean = 685.07 ms, SD = 136.90 ms, d = 2.30[1]). A main effect of epoch (F [2.53, 116.27] = 17.24, $p < .001$, $\eta_p^2 = .27$), confirmed that there was a significant decrease in RT across the epochs. The main effect of group (F (1, 46) = 12.66, $p = .001$, $\eta_p^2 = .22$) confirmed that children with dyslexia were significantly faster on the task compared with the control group overall (Dyslexic group mean = 577.34 ms, SD = 127.81 ms; Control group mean = 708.76 ms, SD = 127.80 ms, d = 1.03). The two groups did not differ in the overall level of procedural learning, as indicated by the non-significant interaction between group and sequence (F [1, 46] = .975, $p = .33$, $\eta_p^2 = .02$). However, a small but significant interaction between group, sequence, and epoch (F (3.11, 143.12) = 2.94, $p = .03$, $\eta_p^2 = .06$) suggested that the groups did differ in the rate of development of procedural learning across the epochs of the task.

5.2 | Correlations by group

Sample sizes in the current study are small, but correlations for each group were examined to see if the pattern of relationships between the measures in the study differed by group. Apart from the expected relationships for reading

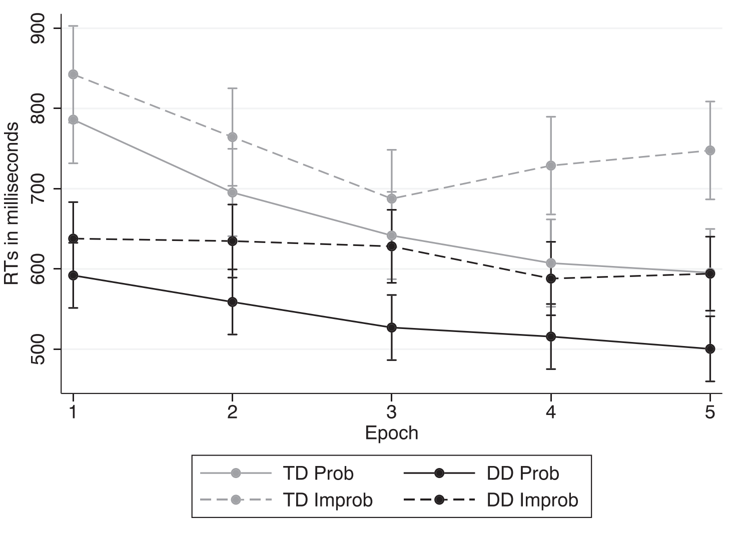

FIGURE 1 Reaction time (RTs) for the probable and improbable sequences by dyslexic (DD) and typically developing control groups (TD), with 95% confidence intervals

measures and for verbal declarative memory measures, correlations between all measures for each group were generally low and similar for the two groups (see Tables 2 and 3 for correlations for each group).

Correlations between measures of verbal declarative memory were larger in the control group than in the group with dyslexia. The control group also showed a moderate correlation between short-term declarative verbal memory (WL-L) and word and non-word reading (*r*'s = .39 and .40, respectively), which was completely absent in the dyslexic group.

Because age was related to word (DD $r = .76$; TD $r = .47$) and non-word reading (DD $r = .65$; TD $r = .47$) in both groups, partial correlations controlling for age were also calculated (see Tables 2 and 3). Using these measures, the difference between the correlations for word reading and short-term verbal declarative memory for the two groups increased (see Figure 2), only remaining positive in the control group (Dyslexic group $r = -.39$; Control group $r = .39$).

6 | DISCUSSION

In this study we compared the performance of a group of children with dyslexia and a typically developing control group matched for reading ability on tasks tapping procedural and declarative learning. This design enabled us to

TABLE 2 Correlations between age and all measures for the dyslexic group ($n = 23$)

	1	2	3	4	5	6	7
1. Age in months		.76*	.65*	.32	.26	.11	−.14
2. TOWRE-2 words	.76*		.81*	.00	.01	−.09	−.06
3. TOWRE-2 non-words	.67*	.65*		.23	.09	.18	−.16
4. WL-L	.32	−.39	.04		.67*	.47*	−.31
5. WL-D	.26	−.29	−.11	.64*		.37	−.16
6. WL-C	.11	−.27	.14	.46*	.36		−.08
7. SRT RT Difference	−.14	.07	−.09	−.28	−.13	−.06	

Note. Simple correlations are above the diagonal and partial correlations controlling for age are below the diagonal.

Abbreviations: WL-L, Word Lists - Learning; WL-D, Word Lists - Delay; WL-C, Word Lists - Consolidation; SRT, serial reaction time task; RT, reaction time. [Correction added on 9 May 2019, after Online publication: In Table 2, Abbreviation list has been added in this current version.]

*$p < .05$.

TABLE 3 Correlations between age and all measures for the control group ($n = 25$)

	1	2	3	4	5	6	7
1. Age in months		.47*	.47*	.14	−.02	.05	.38
2. TOWRE-2 words	.47*		.70*	.41*	.19	.31	.19
3. TOWRE-2 non-words	.47*	.62*		.42*	.18	.22	.08
4. WL-L	.14	.39	.40		.78*	.60*	.09
5. WL-D	−.02	.22	.22	.79*		.71*	.05
6. WL-C	.05	.32	.23	.60*	.72*		.04
7. SRT RT Difference	.38	.02	−.12	.04	.06	.02	

Note. Simple correlations are above the diagonal and partial correlations controlling for age are below the diagonal.

Abbreviations: WL-L, Word Lists - Learning; WL-D, Word Lists - Delay; WL-C, Word Lists - Consolidation; SRT, serial reaction time task; RT, reaction time. [Correction added on 9 May 2019, after Online publication: In Table 3, Abbreviations list has been updated in this current version.]

*$p < .05$.

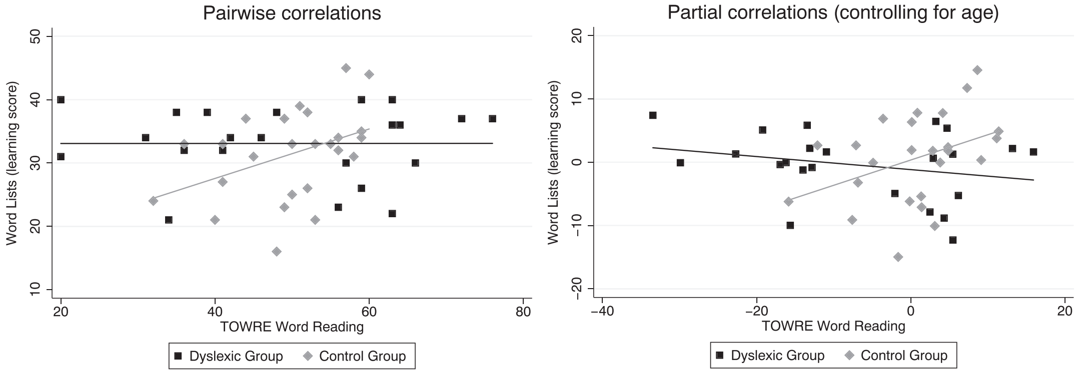

FIGURE 2 Left scatterplot showing relationship between word reading and short-term declarative memory for each group, with linear fit lines. Right plot shows same relationship, but controlling for age

compare children who differ in their ability to learn to read but who have developed equal levels of reading skill. Reading level designs like this can shed light on the causal direction of relationships between memory skills and reading, because differences in task performance cannot be attributed to differences in reading ability.

6.1 | Procedural learning

Overall, we found that children with dyslexia showed comparable levels of procedural learning with typically developing children matched for reading ability. However, there was a small but significant difference in the rate of development of procedural learning over the course of the task between groups. The level of procedural learning in the typically developing group increased during Epoch 4 of the task, as RTs to improbable trials slowed down markedly. This slowing of RTs to improbable sequence trials likely occurs as children inhibit their responses to the probable location in order to respond correctly. By comparison, RTs to improbable trials in the group with dyslexia continued to speed up during Epoch 4. Given that increased speed on improbable trials cannot be influenced by sequence learning, this strongly suggests continued motor learning right through to the late stages of the task in the dyslexic group. Furthermore, the decrease in RTs for both probable and improbable sequence trials for dyslexic children in the first half of the task is less than for typically developing children, suggestive of poorer initial motor learning in the dyslexic group. This pattern of differences between the groups may indicate that extraneous factors, such as impaired coordination or motor learning (Ramus, Pidgeon, & Frith, 2003), influence the performance of children with dyslexia on the serial reaction time tasks. This conjecture is in line with findings from some previous studies in children with dyslexia (Vakil, Lowe, & Goldfus, 2015) and adults (Henderson & Warmington, 2017; Laasonen et al., 2014). Finally, it should be noted that individual differences in procedural learning did not correlate with word or non-word reading in either group.

One possible question raised by this study is whether 7-year old children are capable of managing the task demands of a lengthy SRT task with a complex sequential structure. Children undertaking SRT tasks in studies of procedural learning in dyslexia are typically 8 years of age or older (e.g., Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011). However, children participating in studies of procedural learning in developmental language disorder are often younger. For example, Lum and Bleses (2012) and Lum, Gelgic, and Conti-Ramsden (2010) both examined procedural learning in 7-year old children with developmental language disorder using Nissen and Bullemer's (1987) original 10-item sequence structure. More generally, Meulemans, Van der Linden, and Perruchet (1998) have demonstrated that an SRT task with a complex sequence, interspersing 10 repeating items with six random trials was as capable of eliciting procedural learning in 6-year old children as in adults, whereas children as young as 4 years have been shown to cope well with the demands of a 10-item SRT task (Thomas & Nelson, 2001). In the current study, a game-like, feedback element was included to ensure the task was palatable for young children, encouraging them to try to improve their performance over time. The use of a gamepad as a response mechanism also helped to keep the children focussed and motivated throughout the task and facilitated motor responses.

Critically, our results demonstrate that both the younger control group of typically developing children and the older group of children with dyslexia were able to cope with the demands of the task. First and foremost, both groups showed clear evidence of procedural learning on the task, with faster RTs for probable trials compared with probable trials on every block of the task. Additionally, for both groups, overall facility with the task continued to improve throughout, as evidenced by decreasing RTs for probable trials across epochs right up to the end of the task.

6.2 | Declarative learning

There was no significant difference between children with dyslexia and reading ability matched controls on measures of declarative learning. Impairments on such tasks in children with dyslexia are typically observed in comparison with age-matched typically developing children (Kibby & Cohen, 2008; Menghini, Carlesimo, Marotta, Finzi, & Vicari, 2010; Vellutino & Scanlon, 1985). We attribute the absence of group differences here to the fact that our dyslexic group were considerably older than the controls. Regardless of this, the dyslexic group did not show the same relationship between declarative learning and reading as the control group. The clear positive relationship between declarative learning and both word and non-word reading in the typically developing group was entirely absent in the dyslexic group.

In summary, we found that both typically developing and children with dyslexia matched for reading ability demonstrated equivalent levels of procedural learning on a serial reaction time task. Moreover, performance on the SRT task did not relate to measures of reading in either group. Although declarative learning in the two groups was comparable, differences between the groups were apparent. Declarative learning was related to reading in the typically developing group, whereas no such relationship was found in the dyslexic group. The results in this study do not support the theory that impaired sequence-related procedural learning is behind the pattern of deficits seen in dyslexia.

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ENDNOTE

[1]Cohen's *d* calculated using correlation between means of $r = .96$, correcting for dependence between means with Morris and Deshon's (2002) equation 8.

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APPENDIX A

TABLE A1 Serial reaction time task means and standard deviations for dyslexic and control groups by sequence and epoch

	Dyslexic group (*n* = 23)		Control group (*n* = 25)	
Epoch	Probable	Improbable	Probable	Improbable
1	592.22 (146.71)	637.73 (150.73)	784.91 (205.96)	840.35 (253.04)
2	558.87 (112.97)	632.90 (137.23)	694.50 (151.22)	766.00 (194.01)
3	526.17 (92.54)	626.77 (144.44)	640.52 (153.57)	685.20 (133.41)
4	514.84 (99.11)	590.21 (111.00)	606.06 (112.60)	728.43 (167.53)
5	498.81 (94.65)	595.46 (120.66)	594.07 (113.61)	747.59 (197.76)