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Sequential Implicit Learning Ability Predicts Growth in Reading Skills in Typical Readers and Children with Dyslexia

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ABSTRACT

This study investigated in a longitudinal design how 74 Dutch children with dyslexia and 39 typically developing peers differed in sequential versus spatial implicit learning and overnight consolidation, and it examined whether implicit learning related to (pseudo)word reading development in Grades 5 and 6. The results showed that sequential, but not spatial, learning predicted growth in reading skills in children with and without dyslexia. Sequential implicit learning was also related to growth in pseudoword reading skills during an intervention in children with dyslexia, retrospectively. Furthermore, children with dyslexia had longer reaction times in general but did not differ from typical readers in how well or how quickly they learned either on an implicit learning task or in their overnight consolidation.

An important part of reading instruction involves explicit teaching of correspondences between phonemes and graphemes (Ehri et al., 2001), but there are also aspects of reading acquisition that involve implicit processes, such as learning from context and automatizing reading skills (Nicolson, Fawcett, Brookes, & Needle, 2010). It has been argued that especially implicit learning of sequential information is important for developing fluent reading skills (Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011). Previous studies have found an association between implicit learning and reading abilities. That is, children with higher reading levels performed better on implicit learning tasks than children with lower reading levels (Hedenius, Persson, et al., 2013; Howard, Howard, Japikse, & Eden, 2006). Furthermore, it has been argued that problems with acquiring fluent and accurate reading skills in children with dyslexia and difficulty improving their reading skills during intervention is caused by an underlying deficit in acquiring and retaining implicit information (Nicolson et al., 2010). However, it has not been investigated to what extent implicit learning relates to reading *development* in typical or dyslexic readers. Therefore, we examined sequential and spatial implicit learning in children with dyslexia and typical readers and investigated whether implicit learning performance predicted growth in word and pseudoword reading skills.

So far, only a few studies have linked sequential implicit learning to individual differences in reading skill (Hedenius, Persson, et al., 2013; Howard et al., 2006; Vakil, Lowe, & Goldfus, 2013). A learning task that is commonly used to measure implicit learning is the serial reaction time (SRT) task (first reported by Nissen & Bullemer, 1987). Participants are asked to carry out motor responses as quickly and accurately as possible to a sequence of visual cues, without being aware that this sequence is predictable. Although the reliability of the task has recently been questioned (West, Vadillo, Shanks, & Hulme, 2017), accuracy and response speed on the SRT task have been found to correlate positively with word and pseudoword reading measures (Hedenius, Persson, et al., 2013;

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Howard et al., 2006), even after controlling for rapid naming skills (Howard et al., 2006). Furthermore, learning rate on the SRT task was associated with pseudoword reading rate (Vakil et al., 2013). However, no previous research has examined how implicit learning relates to reading development in a longitudinal design, and thus the direction of the relations remains unclear.

With respect to the association with reading difficulties, a number of studies have examined implicit learning as an underlying deficit in dyslexia (e.g., Lum, Ullman, & Conti-Ramsden, 2013). Lum et al. (2013) showed in a meta-analysis of 14 implicit learning studies that participants with dyslexia were outperformed by typical readers on the SRT task. The authors found a medium-weighted effect size (.449) for the SRT task, but there was substantial heterogeneity between study-level effect sizes (varying from −.710 to 1.172), and not all studies included in the meta-analysis found significant differences between participants with dyslexia and typical readers. This lack of a significant difference between participants with dyslexia and typical readers is also found in more recent implicit learning studies comparing adults (Henderson & Warmington, 2017) or children (Staels & van den Broeck, 2017; Vakil et al., 2013) with and without dyslexia.

An important issue is whether poor performance on the SRT task is due to a more general implicit learning deficit or whether it is restricted to learning sequential information. So far, studies that compared sequential implicit learning—supported by fronto-striatal-cerebellar circuitry—to spatial implicit learning—depending on medial temporal lobe structures (see Howard, Howard, Dennis, Yankovich, & Vaidya, 2004), found that difficulties with implicit learning in people with dyslexia were limited to sequential learning (Howard et al., 2006; Jiménez-Fernández et al., 2011). However, spatial implicit learning has not been related to the development of reading.

The goal of the present study was to examine how implicit learning, in 74 Dutch children with dyslexia and 39 typical readers, is related to the development of reading skills longitudinally. Two types of implicit learning were measured: spatial and sequential implicit learning. Furthermore, to examine multiple stages of learning, both initial learning and overnight consolidation were examined. Consolidation can be described as a later "off-line" phase after initial learning, during which stable memory traces are formed (Robertson, Pascual-Leone, & Miall, 2004). Two previous studies have examined consolidation for sequential implicit learning and found no differences between children with dyslexia and typical readers (Hedenius, Persson, et al., 2013; Henderson & Warmington, 2017). However, Hedenius, Persson, et al. (2013) found differences between the two groups on the 2nd day, after extended practice.

Pseudoword and word reading were included as a reflection of the two reading routes put forward in the dual route model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Moreover, individual differences in implicit learning were related retrospectively to differences in response to a reading intervention, which the children with dyslexia had completed earlier. The following questions were addressed: First, do children with dyslexia and typical readers differ in spatial and sequential implicit learning and overnight consolidation? Second, does performance on implicit learning tasks relate to growth in word and pseudoword reading skills from Grade 5 to Grade 6 in children with dyslexia and typical readers? Because the children with dyslexia were part of a larger longitudinal study on reading development during and after intervention, we were also able to relate implicit learning to previous growth in reading skills during an intervention. Therefore a third question was addressed: Does implicit learning relate to the response to a previously completed reading intervention in children with dyslexia? First, we expected typical readers to outperform children with dyslexia on sequential, but not spatial, learning. Second, we expected a relation specifically between sequential implicit learning and reading skills; better implicit learning skills were expected to be associated with higher reading skills. Third, we expected that children who were better at implicit learning in Grade 5 showed more growth in reading skills from Grade 5 to Grade 6 and (in case of the children with dyslexia) during their reading intervention.

Method

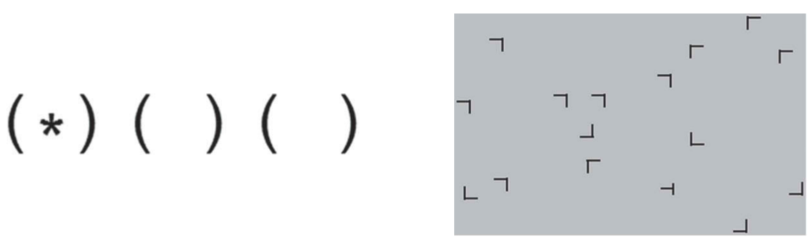
Participants

Participants were 113 fifth-grade children from regular primary schools in the Netherlands, of which 74 had been diagnosed with dyslexia (31 girls, 43 boys; M_{age} = 11 years 4 months, *SD* = 3 months) in Grade 2. Criteria for diagnostics and intervention were established according to a nationally standardized protocol (Blomert, 2006). Children with dyslexia scored within the lowest 10% on standardized reading tests and within the lowest 10% on measures of phonological awareness, rapid naming, or letter knowledge. The 39 typical readers were recruited from four primary schools in the Netherlands (16 girls, 23 boys; M_{age} = 11 years 0 months, *SD* = 2 months). Both groups had average nonverbal cognitive abilities (children with dyslexia: *M* = 98, *SD* = 9.16; Wechsler Intelligence Scale for Children–III–NL, Kort et al., 2005; typical readers: percentile scores *M* = 52.79, *SD* = 30.30; Raven's Progressive Matrices, Raven, Raven, & Court, 1998). Parents had given active consent for participation of their child in the study.

Materials

Experimental tasks

Sequential implicit learning. A SRT task was used to measure sequential implicit learning (Staels & van den Broeck, 2017). The children sat in front of a laptop and rested their right-hand ring, middle, and index fingers on three keys on a QWERTY keyboard. On the screen, three sets of brackets indicated three possible locations where a target stimulus (an asterisk) could appear. The children were instructed to press the key (V, B, or N) corresponding to the position of the target that appeared on the screen as quickly and accurately as possible (see Figure 1a). E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) was used to present stimuli and record reaction times. The task consisted of 12 blocks (Table 1). The task started with a practice block, followed by a random block and a block in which a second-order conditional training and a control sequence of six positions of the stimulus were each presented four times (see Jiménez-Fernández et al., 2011). The order of locations used in the training and the control sequence differed, but both sequences contained a second-order conditional sequence. In Blocks 4–10, the training sequence was repeated 10 times. The control sequence was presented in Block 11, and the task ended with a final block containing the training sequence. There were two indicators for implicit learning: (a) decreasing reaction times from Blocks 4 to 10, and (b) an increase in reaction times between Blocks 10 and 11. Overnight consolidation was measured by comparing performance on the final block of the 1st day to the first block on the 2nd day. Split-half reliability of this task was moderate (typical readers = .67, children with dyslexia = .70).



(a) (b)

Figure 1. (a) Example of the layout of the Serial Reaction Time task. (b) Example of the layout of the Spatial Contextual Cueing task.

Table 1. Experimental Design of the Serial Reaction Time Task

Block	Trials	Order
1	9	Practice phase
2	48	Random without repetitions
3	48	Four training and four control sequences
4–10	420	Training sequence
11	60	Control sequence
12	60	Training sequence

Spatial implicit learning. A spatial contextual cueing (SCC) task was used to measure spatial implicit learning (a paradigm developed by Chun & Jiang, 1998). The stimuli were presented on a laptop with PsychoPy (Peirce, 2007). Children sat in front of the screen and rested their right-hand index and middle fingers on the left and right arrows of the keyboard, respectively. A target item (a letter T that was rotated 90° to the left or the right) appeared. With each target item, 15 distractors were presented (a letter L) that were rotated 0°, 90°, 180°, or 270° (see Figure 1b). Participants were instructed to press the corresponding arrow button as quickly and accurately as possible to indicate whether the target item was rotated to the left or the right. The task consisted of a repeated and a random condition. The repeated condition consisted of spatial layouts that were initially generated randomly and then repeated once during each block, throughout the experiment. The random condition contained spatial layouts that were randomly generated for each block. The task consisted of 15 blocks, each containing 12 repeated and 12 random items. The order of random and repeated items was randomized within blocks. The locations of the distractors in the repeated condition was held constant and thus predicted the location of the target item (but not its rotation). Learning was indicated by a decreasing reaction time for the repeated items over the 15 blocks. Split-half reliability of this task (typical readers = .66, children with dyslexia = .57).

Reading tasks

Reading measures Grades 5 and 6. Reading skill was measured with standardized word and pseudoword reading tasks (Verhoeven & Keuning, 2014). Cards 1 and 2 contained five rows of 30 consonant–vowel–consonant (CVC) and 30 CCV (pseudo)words, respectively. The third and fourth cards consisted of four rows of 30 two-syllable and 30 three- or four-syllable pseudo(words), respectively. Children were asked to read as many items on a card as possible in 1 min without making mistakes. To give equal weight to each card, the number of correctly read items was counted and converted to *z* scores. These scores were averaged across the four cards, resulting in one score for word and one for pseudoword reading. The reading test was administered at the end of each grade. The measure of growth was the increase in correctly read items from Grade 5 to Grade 6. Internal reliability was excellent: Cronbach's alpha for the four word reading cards was .96, .95, .96, and .96 and for the pseudoword reading cards was .96, .96, .97, and .93, respectively (Verhoeven & Keuning, 2017).

Reading measures during the reading intervention. During the reading intervention, word and pseudoword reading were assessed with two standardized tests: the One Minute Test (Een Minuut Test; Brus & Voeten, 1979) and the Klepel (van den Bos, Lutje Spelberg, Scheepstra, & De Vries, 1994). Both tasks consisted of 112 CVC, CCV, two-syllable, and three-syllable words or pseudo-words. Children were asked to read as many items as possible in 1 (word reading task) or 2 min (pseudoword reading task) without making mistakes. Children's scores were the number of items read correctly. The Een Minuut Test R_n reliability varies between .90 and .94 and between .89 and .94 for the Klepel. During the intervention, progress in reading skills was monitored four times. Mixed models were used to model growth in word and pseudoword reading. The slope of these models was the measure of response to intervention.

Procedure

The children with dyslexia had all followed a reading intervention that started in Grade 2 and was completed in Grade 4. The intervention was phonics based and consisted of 50 individual sessions of 45 min with a clinician at the child's school (Tilanus, Segers, & Verhoeven, 2016). In Grade 5, all children were tested individually in a quiet room at their school. The measure of nonverbal cognitive ability was assessed groupwise for the typical readers. The tests were administered in two consecutive 40-min sessions. On Day 1, the SRT and the SCC task were administered, as well as the pseudoword reading task. On Day 2, the SRT and SCC task were administered a second time to measure consolidation, as well as the word reading task. The durations of the SRT task and SCC task were about 8 to 10 min and 15 min, respectively. The reading tests were administered a second time at the end of Grade 6.

Results

To answer the first question, accuracy and response speed on the implicit learning tasks and consolidation were examined in both groups. For all reaction time analyses, inaccurate responses were removed. Because the reaction time data were skewed, median reaction times for each block were used. Reaction times per block for the sequential and spatial implicit learning task are shown in Figures 2 and 3.

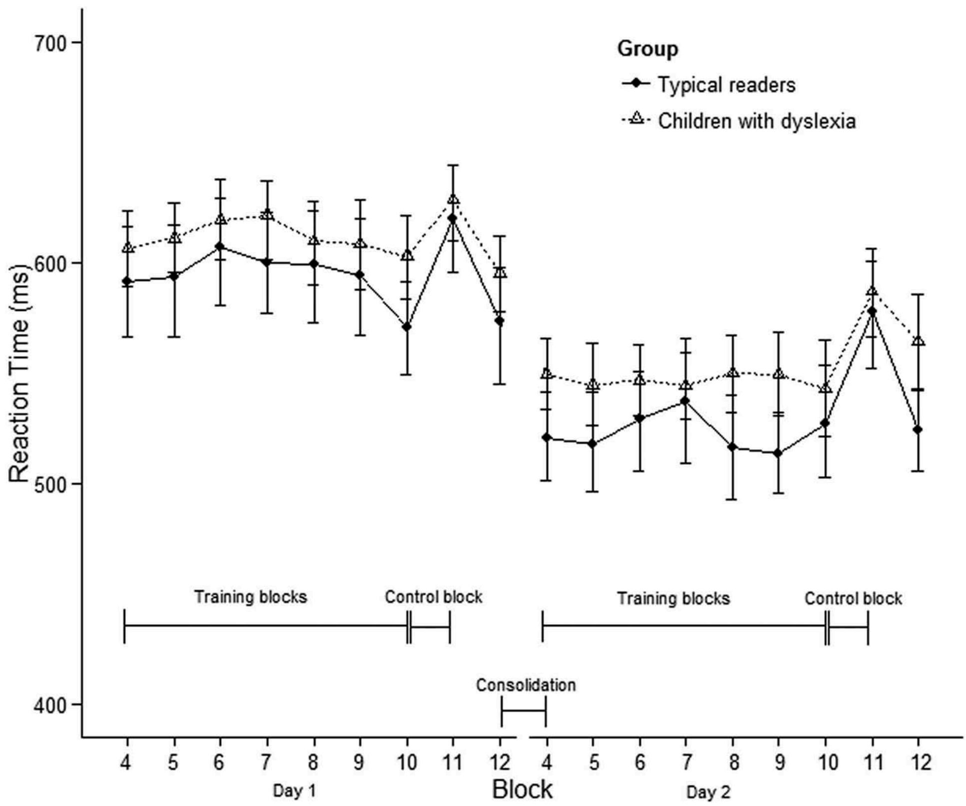


Figure 2. Group average of median reaction times on the sequential learning task on Days 1 and 2. *Note*. The error bars represent standard errors of the mean.

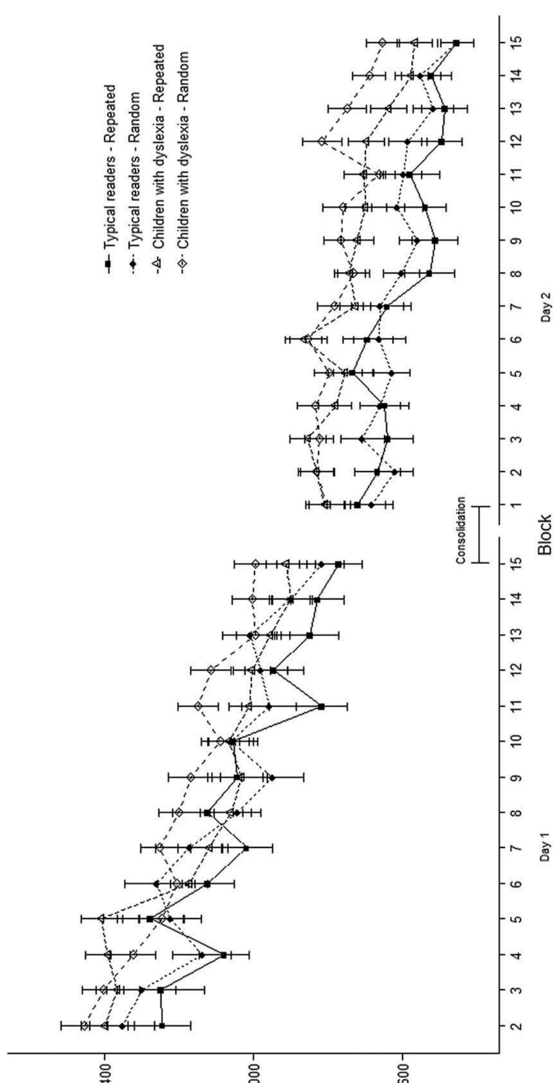


Figure 3. Group average of median reaction times on the spatial learning task for the repeated and random conditions on Days 1 and 2. *Note*. The error bars represent standard errors of the mean.

Sequential learning

Accuracy on Day 1

Response accuracy did not differ between groups, $t(67.55) = -0.19$, $p = .85$, $d = 0.04$ (typical readers: $M = 89.21\%$, $SD = 12.53$; children with dyslexia: $M = 89.65\%$, $SD = 10.30$). To ensure that the results for the reaction times were not unduly influenced by data from children who did not understood the task or were not motivated to complete it, we followed Hsu and Bishop (2014) in including children for further analyses only if they scored at least 70% correct. Two typical readers and five children with dyslexia scored below 70% correct on Day 1, and data from these children were therefore excluded from the analyses of reaction times.

Reaction times on Day 1

Changes in reaction times over the seven training blocks were taken as a measure of learning rate and were modeled using the lme4 package, version 1.1–7 (Bates, Maechler, Bolker, & Walker, 2014) in R (R Core Team, 2013), using a maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013). Model fits were compared with the analysis of variance function of the *stats* package. Linear, quadratic, and cubic terms were added as fixed effects to model the shape of learning. The learning curve of the training phase (block) was modeled, as well as the response increase between the final training block and the block containing the control sequence (response increase). The final model on both days included group, block, a cubic term, response increase, the Block × Group and Response Increase × Group interactions as fixed effects, and a random intercept and random slopes. Results on Day 1 showed that children with dyslexia were significantly slower than typical readers in general ($\beta = 52.30$, $p = .03$). There was also an effect of block ($\beta = 12.45$, $p = .02$), indicating that reaction times decreased over blocks for both groups. The interaction between group and block was not significant ($\beta = -2.97$, $p = .52$). The increase in reaction time between the final training block and the control block was significant ($\beta = 28.48$, $p = .02$) but did not differ between groups ($\beta = 9.72$, $p = .42$).

Accuracy on Day 2

Overall, accuracy on Day 2 did not differ significantly between groups, $t(77.14) = 0.75$, $p = .46$, $d = 0.15$ (typical readers: $M = 90.53\%$, $SD = 14.39$; dyslexics: $M = 88.40\%$, $SD = 14.33$). From the children who scored below 70% on Day 1, one typical reader and four children with dyslexia still scored below 70% correct on Day 2. In addition, two typical readers and four children with dyslexia now also scored below 70% correct and were removed from further reaction time analyses.

Reaction times on Day 2

On Day 2 there was a significant effect of group ($\beta = 48.77$, $p = .03$), indicating that children with dyslexia were still slower than the typical readers in general. The effect of block was also significant ($\beta = -176.59$, $p < .001$), meaning that reaction times decreased over blocks. The interaction between block and group was not significant ($\beta = -1.15$, $p = .63$). The response increase between the final training block and the control block was significant ($\beta = 47.73$, $p < .001$) but did not differ between groups ($\beta = 6.64$, $p = .55$).

Overnight consolidation

The effect of overnight consolidation was investigated by comparing reaction times of the final block on Day 1 (Block 12) to the first block of Day 2 (Block 4). The final model included a random intercept and block and group as fixed effects. Adding the Group × Block interaction did not improve the model fit, $\chi^2(1) = 0.74$, $p = .39$. Reaction times decreased between the final block on Day 1 and the first block on Day 2 ($\beta = 40.74$, $p = .002$). The children with dyslexia were slower overall than the typical readers ($\beta = 54.33$, $p = .002$).

Spatial learning

Accuracy on Day 1

On the spatial task, the groups did not differ significantly in their mean percentage correct trials, $t(87.92) = 1.15$, $p = .25$, $d = 0.14$ (typical readers: $M = 85.56\%$, $SD = 7.25$, children with dyslexia: $M = 86.53\%$, $SD = 6.67$). Two children with dyslexia scored below 70%, and were not included in the reaction time analyses.

Reaction times on Day 1

The final model on Day 1 and 2 for examining learning rate included block, group, condition, the Block × Condition interaction, a quadratic term as fixed effects, and a random intercept and random slopes. There was a significant effect of block ($\beta = -79.50$, $p < .001$), indicating that reaction times decreased over blocks for both groups. There was also a significant effect of group ($\beta = 110.99$, $p = .04$). Overall, children with dyslexia were significantly slower than typical readers. The effect of condition was not significant (repeated vs. random = −20.25, $p = .56$), the random condition did not differ from the repeated condition. However, the interaction between block and condition was significant and showed that the learning rate for the random condition was slower than the learning rate for the repeated condition ($\beta = 9.70$, $p = .009$).

Accuracy on Day 2

None of the children scored below 70% correct. On Day 2, children with dyslexia ($M = 94\%$, $SD = 23.72$) were still as accurate as the typical readers ($M = 95\%$, $SD = 20.76$), $t(96.38) = 0.22$, $p = .10$, $d = 6.56$.

Reaction times on Day 2

The significant effect of block indicated that reaction times still decreased on Day 2 ($\beta = -18.16$, $p = .02$). The effect of group was also significant on Day 2 ($\beta = 143.68$, $p = .004$), meaning that children with dyslexia still responded more slowly than typical readers. The effect of condition was not significant (repeated vs. random = −30.74, $p = .17$), but the Block × Condition interaction was significant ($\beta = 8.83$, $p < .001$). The reaction times in the repeated condition still decreased more than the reaction times in the random condition.

Overnight consolidation

The reaction times of the final block on Day 1 and the first block on Day 2 were compared as a measure of overnight consolidation. The final model included a random intercept and block, condition, and group as fixed effects. The main effects of group, block, and condition and the interactions between Group × Condition and Block × Group × Condition were not significant. There was a significant interaction between Block × Condition ($\beta = 10.26$, $p = .04$), showing that there was a larger decrease in reaction times for the repeated blocks.

Association of implicit learning with reading skills

To answer the second research question, the intercept and slope of the sequential and spatial learning task were related to reading skill. In this case, the intercept is considered to represent the overall performance speed on the task, whereas the slope is considered to represent learning (i.e., the decrease in reaction time over the training blocks). These two measures were related to three reading measures: (a) reading scores in Grade 5, (b) growth in reading skills from Grade 5 to Grade 6, and (c) response to intervention in children with dyslexia. On average, children with dyslexia still scored more than 2 *SD* below the mean of the typical readers on all reading tasks (Table 2).

Table 2. Descriptives of Raw Scores on the Word and Pseudoword Reading Tests for Typical Readers and Children With Dyslexia

		Typical Readers[a]		Children With Dyslexia[b]			
		M	*SD*	*M*	*SD*	*t*	*d*
Grade 5	Words	354.87	42.06	188.33	47.77	18.37**	3.70
	Pseudowords	227.08	38.60	97.99	28.82	18.39**	3.79
Grade 6	Words	376.53	49.77	213.84	49.80	16.04**	3.27
	Pseudowords	252.28	45.48	114.81	34.86	15.97**	3.39

[a]$n = 39$. [b]$n = 74$.
**$p < .001$.

First, the intercept of the sequential learning task significantly predicted word and pseudoword reading skills in Grade 5 (Table 3). The interactions with group did not significantly add to the prediction of word ($\Delta R^2 = .001$, $p = .74$) or pseudoword reading ($\Delta R^2 = .003$, $p = .45$).

With regard to the spatial learning task, neither the intercept nor the slope significantly predicted word ($\Delta R^2 = .01$; intercept $\beta = -.01$, $p = .83$; slope $\beta = -.07$, $p = .27$) or pseudoword reading ($\Delta R^2 = .01$; intercept $\beta = -.02$, $p = .68$; slope $\beta = -.01$, $p = .90$).

Second, in addition to the strong autoregressive effect of reading in Grade 5 on reading in Grade 6, the SRT slope explained a small but significant proportion of variance in reading scores (Table 4). The interactions with group were not significant (words $\Delta R^2 = .24$, $p = .13$; pseudowords $\Delta R^2 = .24$, $p = .81$). For the spatial task, there were no significant effects on growth in word ($\Delta R^2 = .00$; intercept $\beta = .02$, $p = .71$; slope $\beta = .06$, $p = .35$) or pseudoword reading ($\Delta R^2 = .00$; intercept $\beta = .03$, $p = .51$; slope $\beta = -.001$, $p = .99$).

Association of implicit learning with response to intervention

With respect to the third question, retrospectively, a significant association was found between growth in pseudowords reading during the intervention and sequential implicit learning as reflected in the decrease in reaction times on the SRT task ($r = -.24$, $p < .05$). Children with more growth in pseudoword reading during the intervention also had a faster learning rate on the sequential learning task (Table 5).

Table 3. Regression Analysis With Sequential Procedural Learning (SRT Intercept and Slope) as Predictors for Reading in Grade 5

		Grade 5 Words			*Grade 5 Pseudowords*		
		B	*SE*	β	*B*	*SE*	β
Step 1							
	Group	−1.78	.09	−.87**	−2.86	.85	−1.41***
Step 2							
	SRT Intercept	−.002	.001	−.19**	−.002	.001	−.23**
	SRT Slope	−.088	.006	−.07	−.01	.01	−.06
Total R^2 adj.				.77***			.80***

Note. SRT = serial reaction time.
**$p < .01$. ***$p < .001$.

Table 4. Regression Analysis With Sequential Procedural Learning (SRT Intercept and Slope) as Predictors for Reading in Grade 6

		Grade 6 Words			*Grade 6 Pseudowords*		
		B	*SE*	β	*B*	*SE*	β
Step 1							
	Group	−.09	.11	.05	.14	.11	.04
	Grade 5	.91	.05	.93***	.94	.06	.93***
Step 2							
	SRT Intercept	−.00	.00	−.04	00	.00	.01
	SRT Slope	−.01	.003	−.09**	−.008	.003	−.07**
Total R^2 adj.				.94***			.94***

Note: Words $\Delta R^2 = .03$**; pseudowords $\Delta R^2 = .02$**. SRT = serial reaction time.
**$p < .01$. ***$p < .001$.

Table 5. Pearson Correlations Between Reading Measures and Procedural Learning (SRT/SCC) for Typical Readers and Children With Dyslexia

	1	2	3	4	5	6	7	8
1. SRT Intercept	—	−.09	.49**	.23	−.38*	−.31	−.15	−.17
2. SRT Slope	−.59**	—	.08	−.18	.19	.12	−.10	.04
3. SCC Intercept	.25**	−.04	—	.34*	−.31	−.29	−.10	−.04
4. SCC Slope	.09	−.13	.46**	—	−.42**	−.27	−.22	−.23
5. Grade 5 words	−.26*	−.06	−.12	−.04	—	.84**	.81**	.84**
6. Grade 5 pseudowords	−.25*	−.04	−.16	.14	.75*	—	.67**	.86**
7. Grade 6 words	−.24*	−.004	−.09	−.004	.90**	.71**	—	.81**
8. Grade 6 pseudowords	−.21	−.14	−.12	.16	.66**	.88**	.75**	—

Note. Typical readers (n = 38) are above the diagonal, and children with dyslexia (n = 74) are below the diagonal.
*p < .05. **p < .01.

Discussion

In this study, we first examined how children with dyslexia performed on a sequential and a spatial implicit learning task compared to typical readers. We found no significant differences in learning rate on the sequential or spatial task in children with dyslexia and typical readers, in line with more recent literature (Schmalz, Altoè, & Mulatti, 2017; Staels & van den Broeck, 2017; Vakil et al., 2013). However, the standardized mean difference effect size of 0.33, 95% confidence interval [−0.06, 0.72], for the sequential implicit learning task, was in the same direction as in the meta-analysis by Lum et al. (2013). As argued by Lum et al., the number of trials, sequence complexity, or age may be factors that possibly account for differences between studies. Even though accuracy and learning rate did not differ from typical readers in our study, children with dyslexia did overall respond more slowly on both tasks. Based on these implicit learning tasks it is unclear what causes these slower reaction times (e.g., processing speed, memory retrieval, or a slower motor response). However, previous research has shown that children with dyslexia are also slower in lexical retrieval, often measured with rapid naming tasks (Norton & Wolf, 2012) and retrieval of facts (De Smedt, Taylor, Archibald, & Ansari, 2010).

Second, we examined whether performance on the implicit learning tasks predicted reading performance. In line with previous findings, overall reaction time on the sequential task for both children with dyslexia and typical readers correlated with reading skill (Howard et al., 2006). The current study adds to this that sequential implicit learning was found to contribute to development of reading skills: Over and above the strong autoregressive effect of reading in Grade 5, reading in Grade 6 was predicted by sequential, but not spatial, implicit learning rate. How quickly the children were able to learn implicit sequential information related to their growth in reading skills, both in children with dyslexia and typical readers.

Although implicit learning was measured about one year after children with dyslexia had completed the intervention, it still correlated with growth in pseudoword, but not word, reading skills during the intervention. Children who showed more growth in pseudoword reading during the intervention were faster learners on the sequential implicit learning task. A possible explanation would be that there was more to gain in pseudoword reading than in word reading skills and therefore implicit learning skills were related only to pseudoword reading skills. However, this was not the case in the current sample. Children showed even more growth in word reading than in pseudoword reading skills. Another explanation would be that because children had never seen the pseudowords before and had to apply rules for grapheme-phoneme mappings (i.e., reading via the indirect route). Computation of phonology for these novel words and forming new orthographic representations might depend more on implicit learning skills than word recognition (see Hedenius, Ullman, Alm, Jennische, & Persson, 2013).

Furthermore, in line with the two previous studies that examined overnight improvements due to memory consolidation of sequential implicit learning (Hedenius, Persson, et al., 2013; Henderson & Warmington, 2017), we found no differences in overnight consolidation between children with dyslexia and typical readers. According to Robertson et al. (2004), overnight consolidation is not specific to sequence learning but may also extend to other types of implicit learning. In our study, this was shown by a consolidation effect for the spatial learning task in both typical readers and children with dyslexia.

Future research should examine the association between implicit learning and response to intervention prospectively, rather than retrospectively, and focus on the issue of domain-general versus domain-specific aspects of implicit learning by incorporating phonological information in the implicit learning task.

In conclusion, no differences in how well or how quickly they learned were found between 11-year-old children with dyslexia and typical readers in sequential or spatial implicit learning. Implicit learning, however, did predict reading development from Grade 5 to Grade 6, both in children with dyslexia and in typical readers, and predicted response to intervention in children with dyslexia.

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