Intact first- and second-order implicit sequence learning in secondary-school-aged children with developmental dyslexia

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We examined the influence of task complexity on implicit sequence learning in secondary-school-aged children with developmental dyslexia (DD). This was done to determine whether automatization problems in reading extend to the automatization of all skill and depend on the complexity of the to-be-learned skill. A total of 28 dyslexic children between 12 and 15 years and 28 matched control children carried out two serial reaction time tasks using a first-order conditional (FOC) and second-order conditional (SOC) sequence. In both tasks, children incidentally learned a sequence of hidden target positions, but whereas FOC sequence learning could be based on knowledge about the immediate preceding position, SOC sequence learning required more complex knowledge about the previous two positions. The results demonstrated that sequence learning was highly comparable in dyslexic and control children, regardless of the sequence complexity. This shows that implicit sequence learning, as manifested in the present study, is maintained in DD and is unrelated to task complexity. We suggest that previous reports of sequence-learning deficits in DD can be accounted for by attenuated explicit sequence learning, possibly related to malfunctions in prefrontal processing. The present findings indicate that deficits in skill learning and automatization in DD are not general in nature, but task dependent.

Keywords: Implicit learning; Developmental dyslexia; Sequence learning; Serial reaction time task; Skill learning.

In the present study, we examined the influence of task complexity on skill learning and automatization in secondary-school-aged children with developmental dyslexia (DD). This was done to determine whether automatization problems in reading extend to the automatization of all skill and depend on the complexity of the to-be-learned skill. The disorder has a genetic origin and persists into adulthood, although specialized treatment and compensatory strategies may reduce literacy difficulties to some extent (e.g., Felton, Naylor, & Wood, 1990; Scarborough, 1990; Shaywitz et al., 1995).

At present, the exact underlying causes of dyslexia remain heavily debated. Despite ample behavioral and neurological studies, there is no unitary theory that can account for all of the observed deficits in cognitive and neurological processing in dyslexia (for reviews, see e.g., Moores, 2004; Ramus et al., 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Most researchers nowadays agree that the core characteristic of dyslexia involves a deficit in phonological processing. Dyslexics are presumed to have an impaired sensitivity to the sound structure of language (phonological awareness), which affects their ability to isolate and manipulate the constituent
sounds of speech (phonemic awareness). During early schooling, poor phonological skill will hamper the learning of the correspondence between phonemes and visual symbols (graphemes), like written letters (e.g., Snowling, 2000). As a result, “the automatization of word identification (reading) and/or spelling does not develop or does so very incompletely or with great difficulty” (The Committee on Dyslexia of the Health Council of the Netherlands; in Gersons-Wolfensberger & Ruijssenaars, 1997).

Although a phonological deficit, possibly rooted in left-hemispheric perisylvian dysfunction, is not disputed, a number of researchers claim it to be part of a more extended, general sensory dysfunction. In this line, the magnocellular hypothesis suggests that reading difficulties in dyslexia can be explained by abnormalities in auditory and/or visual magnocellular pathways (for a review see, e.g., Stein & Walsh, 1997). Alternatively, based on the observation that motor problems often coincide with sensory and literacy difficulties, it has been proposed that dyslexics suffer from mild cerebellar dysfunction (e.g., Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 2001). Such subtle cerebellar dysfunction is also predicted by the magnocellular hypothesis (because of massive projection of the magnocellular systems to the cerebellum), but the cerebellar deficit hypothesis translates cerebellar impairment into general difficulties in motor control and skill automatization, including phonological and literacy skill. This postulation is based on the observation that dyslexic children perform worse on a variety of gross motor tasks carried out under dual-task conditions (Nicholson & Fawcett, 1990). Because motor performance is spared under single-task conditions, when attentional resources can be fully applied, it is put forward that children with DD can overcome automatization deficits (to a certain degree) by using conscious compensation strategies.

The idea that automatization problems in reading observed in DD extend to the automatization of all new cognitive and motor skills, as postulated by the cerebellar deficit hypothesis, is still highly controversial. A number of studies have investigated this issue using the serial reaction time task (SRT task; Nissen & Bullemer, 1987), a popular paradigm used to study skill learning (for reviews see, e.g., Clegg, DiGirolamo, & Keefe; 1998; Robertson, 2007). In a prototypical SRT task, participants have to react as fast as possible to a target appearing in one of four horizontal positions by pressing a spatially corresponding response key. Unbeknown to the participants, the target position follows a regular sequence (for instance 132342134142, with the numbers 1 to 4 referring to the positions from left to right). With training of the regular sequence, reaction times (RTs) gradually decrease over sequenced blocks (practice effects). To determine to what extent practice effects involve learning of the specific sequence of events (and not merely sequence-unrelated learning, like the enhanced learning of the stimulus–response mapping, a better understanding of instructions, etc.), the regular sequence is omitted after a sufficient amount of training and is replaced by a random sequence during a block of trials. This results in a sudden increase in RTs and/or error rates (sequence-learning effect).

By analogy with skill learning, sequence learning in the SRT task is presumed to primarily capture implicit learning processes that take place outside conscious control. Although no task is process-pure (e.g., Destrebecqz & Cleeremans, 2001), learning in the SRT task is called implicit because the acquisition of sequence knowledge (a) occurs in the absence of explicit learning instructions (incidental learning) and (b) is also observed in participants who perform poorly on measures of explicit awareness. At present, there is no consensus about the exact definition of implicit learning or the best method to assess awareness (for reviews see, e.g., Cleeremans, Destrebecqz, & Boyer, 1998; Freisch & Rünger, 2003; Shanks & St. John, 1994). Most researchers agree that implicit learning needs to occur incidentally, with the resulting knowledge being difficult to express (see Cleeremans et al., 1998).

Because participants carrying out a SRT task respond to a sequence of visual stimuli by executing a corresponding sequence of motor responses (finger movements), both cognitive (perceptual) and motor aspects contribute to the acquisition of sequence knowledge (e.g., Deroost & Soetens, 2006a, 2006b). This renders the paradigm particularly suitable to investigate possible impairments in learning and automatization of cognitive and motor skill in DD. Interestingly, clinical and neuroimaging evidence suggest that the cerebellum, as part of the cortico-cerebellar network, plays a critical role in the automatization of sequential skill memories as acquired in the SRT task (see, e.g., Doyon, Penhune, & Ungerleider, 2003; Torriero, Olivieri, Koch, Caltagirone, & Petrosini, 2004). Therefore, a disruption of sequence learning in dyslexia could support the notion of a general impairment in skill automatization related to subtle cerebellar dysfunction, as postulated by the cerebellar deficit hypothesis.

Yet, the few studies on implicit sequence learning in dyslexia have yielded mixed results. Whereas some authors reported reduced motor sequence learning in dyslexic children (Vicari et al., 2005) and adults (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Stoodley, Harrison, & Stein, 2006), other researchers observed intact sequence learning in adult dyslexics (Kelly, Griffiths, & Fritz, 2002; Rüsseler, Gerth, & Münte, 2006).

Rüsseler et al. (2006) remarked that differences in sample selection, details of the experimental design, and statistical characteristics of the sequences might account for the divergent findings of sequence-learning performance in dyslexia. Indeed, the two studies reporting intact sequence learning were exclusively carried out with an adult sample of dyslexics (Kelly et al., 2002; Rüsseler et al., 2006). Some authors suggest that the absence of sequence-learning deficits in adults are due to the use of compensation strategies enabling them to overcome certain impairments (Vicari et al., 2005). Although the exact nature and function of such compensation strategies are yet to be determined, this emphasizes the need
for additional studies carried out on children. In the current study, sequence learning was examined in secondary-school-aged children between 12 and 15 years. According to our knowledge, this population has never been investigated before in previous studies on sequence learning in dyslexia. The age group examined in our study is also slightly older than the 11- to 12-year-olds tested by Vicari et al., with a larger age range, making it interesting to examine the robustness of sequence-learning deficits, possibly related to changes in compensation strategies.

Another important factor that may explain the equivocal results of sequence-learning deficits in dyslexia is the statistical complexity of the sequences, which varied between the different studies. Distinct learning mechanisms have been proposed to underlie sequence learning in the SRT task (for reviews, see Cleeremans & Jiménez, 1998; Perruchet & Pacton, 2006). Learning of the sequence 1323413412, for instance, can be based on general, abstract rules, such as “repetitions never occur” (rule-based account; e.g., Lewicki, Hill, & Bizot, 1988). Participants can also learn by decomposing the sequence into fragments or chunks, such as bigrams (13) or trigrams (132; chunk-based account; e.g., Koch & Hoffmann, 2000). In addition, learning can rely on statistical computations carried out on the structural properties of the sequence (statistical account). Although different implicit-learning mechanisms can cooperatively contribute to sequence learning, the statistical view of learning has received most support (see, e.g., Hunt & Aslin, 2001; Jiménez, 2008; Reed & Johnson, 1994; Remillard & Clark, 2001).

According to the statistical account, participants acquire different types of statistical or structural knowledge during implicit sequence learning. For instance, learning of simple frequency information is possible when some elements in a sequence occur more often than others. On a somewhat higher, first-order level, learning when some elements in a sequence occur more often than others (the probability is .67 for transitions 13, 21, 34, and 42, but only .33 for transitions 14, 23, 32, and 41), while some first-order transitions never occur (such as 12, 24, 31, and 43). Sequences containing predictive first-order information are called first-order conditional sequences or FOC sequences. In the present study, learning of the FOC sequence 13234213412 was compared with learning of a second-order conditional sequence or SOC sequence 121342314324. A SOC sequence contains no predictive first-order information (all first-order transitions 12, 13, 14, 21, 23, etc., occur equally often). However, because each first-order transition is followed by a unique position in the sequence (e.g., after the transition 12 only position 1 can occur), the sequence is predictive on second order. Accordingly, whereas learning of FOC sequences can be based on first-order information about the immediate preceding position, SOC sequence learning requires more complex second-order knowledge about the previous two positions in order to predict an upcoming position in the sequence.

It is typically observed that higher order transitions are more difficult to acquire in the SRT task than lower order transitions (e.g., Deroost, Kerckhofs, Coene, Wijnants, & Soetens, 2006; Deroost & Soetens, 2006b; Reed & Johnson, 1994; Remillard & Clark, 2001; Soetens, Melis, & Notebaert, 2005). Differences in the statistical complexity of the sequences may therefore explain the conflicting findings of sequence learning in dyslexia. According to Howard et al. (2006), dyslexics are especially disrupted in implicit learning of higher order information. The authors reported impaired learning of sequences that relied on second order information, because sequenced stimuli were alternated with random stimuli (r, such as 1r2r3r4r; 1r2r4r3r, etc.). It remains to be determined to what extent sequence learning in DD indeed depends on the statistical properties of the sequence information. The Howard et al. study did not include a manipulation of the statistical properties of the sequence structure. In order to obtain more conclusive evidence for the influence of statistical structure on sequence learning in DD, it is necessary to directly manipulate the statistical properties of the sequences. This was the main purpose of the current study, in which we compared learning of first-order and second-order transitions in dyslexic children.

If sequence-learning deficits are specifically related to higher order learning, as put forward by Howard et al. (2006), we expect learning deficits in dyslexic children to be more manifest in second-order learning than in first-order learning. On the other hand, if impairments in sequence learning are observed in dyslexics in both first- and second-order learning, this would indicate that deficits in sequence learning in dyslexia are general in nature and are unrelated to the structural properties of the sequence.

METHOD

Participants

A total of 56 pupils between 12 and 15 years were recruited from a Catholic secondary school in Belgium. A total of 28 children (11 male and 17 female; with an average age of 13.5 years; $SD = 1.23$) were clinically diagnosed by an educational psychologist as having DD. They all followed specialized treatment, with an average of 2.9 years ($SD = 2.1$). Children with comorbidity with attention-deficit/hyperactivity disorder (ADHD) were excluded from participation. The remaining 28 children comprised the control group, matched for sex (11 male and 17 female), age (range $M = 13.6$ years, $SD = 1.16$) and level of education (see Table 1).

Informed consent was obtained from the children’s parents and school in accordance with the Ethics Committee of the Vrije Universiteit Brussel (VUB).
Design and procedure

Testing took place in a private classroom in the presence of the experimenter. Each child participated in three different sessions, with sessions being separated by one week.

Literacy test

The first session started with the administration of a number of subtests of the Dutch version of the Dyslexic Screening Test (DST-NL; Fawcett & Nicolson, 1996; Dutch version by Kort et al., 2005). The DST is a first-step screening instrument used to assess the risk of being dyslexic in children between 6.6 years and 16.6 years. The test comprises 11 subtests measuring literacy skills, phonological awareness and verbal memory, motor skill and balance, and memory retrieval fluency. In the present study, all children were administered 7 of the 11 subtests of the DST: (a) 5 subtests determining literacy skill: Rapid Naming A and B (Subtest 1A to 1B), Word Reading (Subtest 3), Two Minute Spelling (Subtest 6), Nonsense Passage Reading A and B (Subtest 8A to 8B), and One Minute Writing (Subtest 9); (b) and 2 subtests assessing working memory: Phonemic Segmentation A and B (Subtest 5A to 5B) and Backwards Digit Span (Subtest 7). Subsequently, the psycholinguistic quotient (PLQ) was determined for each child based on the norm scores of the 5 literacy skills subtests. Children obtaining a PLQ equal to or below the standard cutoff score of 84 are considered to have a high risk for being dyslexic. Table 1 shows that the DD and control groups differed significantly on all administered literacy and working memory subtests of the DST. As expected, children with DD obtained a significant lower PLQ-score than did controls.

Sequence learning

During the second and third sessions, all children executed the first-order and second-order SRT tasks, with the order of tasks being counterbalanced over sessions. The SRT tasks were run on a Pentium 4 personal computer with 17-inch screen, using E-prime Version 1.1, Service Pack 3 software (Schneider, Eschman, & Zuccolotto, 2002). The target stimulus consisted of a black dot of 8 mm diameter (or 0.8° visual angle with a viewing distance of approximately 60 cm), appearing in one of four horizontally aligned squares of side 1.5 cm (or 1.4° visual angle) that acted as location markers. The distance between adjacent stimulus locations measured 2.5 cm (or 2.4° visual angle). The children were instructed to react to the target position by pressing the “c,” “v,” “b,” and “n” key with the left middle finger, left index finger, right index finger, and right middle finger for a leftmost, left, right, and rightmost target, respectively. Instructions stressed speed as well as accuracy. RTs and accuracy were recorded on each trial. In case of an incorrect response, the word “Error” was presented for 750 ms. No error corrections were possible. The subsequent target appeared after a response–stimulus interval of 50 ms.

The only difference between the two tasks concerned the statistical structure of the sequences used. We established learning of the FOC sequence 13242134142 in the FOC SRT task and learning of the SOC sequence 1213421342 in the SOC SRT task. The FOC and SOC

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**TABLE 1**

Differences in demographic variables and norm scores on the Dutch Dyslexic-Screening Test between children with DD and controls

<table>
<thead>
<tr>
<th>Effect measure</th>
<th>DD (N = 28) Mean ± SD</th>
<th>Controls (N = 28) Mean ± SD</th>
<th>Test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>11.5 ± 17.9</td>
<td>11.5 ± 17.9</td>
<td>^2(1) = 0</td>
<td>.523</td>
</tr>
<tr>
<td>Age</td>
<td>13.5 ± 1.23</td>
<td>13.6 ± 1.16</td>
<td>t(54) = 0.28</td>
<td>.473</td>
</tr>
<tr>
<td>Education level</td>
<td>High 11</td>
<td>Medium 16</td>
<td>Low 1</td>
<td>1</td>
</tr>
<tr>
<td>PLQ</td>
<td>84.8 ± 9.87</td>
<td>107.9 ± 12.09</td>
<td>t(54) = 7.84</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Rapid Naming A</td>
<td>9.2 ± 2.29</td>
<td>11.9 ± 2.42</td>
<td>t(54) = 4.26</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Rapid Naming B</td>
<td>8.3 ± 2.73</td>
<td>10.6 ± 2.39</td>
<td>t(54) = 3.38</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Word Reading</td>
<td>6.7 ± 1.44</td>
<td>10.8 ± 1.76</td>
<td>t(54) = 9.55</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Phonemic Segmentation A</td>
<td>9.9 ± 2.26</td>
<td>11.8 ± 0.79</td>
<td>t(54) = 4.07</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Phonemic Segmentation B</td>
<td>7.6 ± 1.47</td>
<td>10.2 ± 2.04</td>
<td>t(54) = 5.34</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Two Minute Spelling</td>
<td>7.3 ± 1.48</td>
<td>10.2 ± 1.48</td>
<td>t(54) = 6.08</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Backwards Digit Span</td>
<td>8.9 ± 2.49</td>
<td>11.1 ± 2.49</td>
<td>t(54) = 3.43</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Nonsense Passage Reading A</td>
<td>7.0 ± 3.06</td>
<td>10.7 ± 3.06</td>
<td>t(54) = 5.39</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Nonsense Passage Reading B</td>
<td>6.9 ± 2.17</td>
<td>11.1 ± 2.17</td>
<td>t(54) = 7.53</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>One Minute Writing</td>
<td>9.3 ± 2.32</td>
<td>11.8 ± 2.32</td>
<td>t(54) = 4.23</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Note. Dutch Dyslexic-Screening Test (Kort et al., 2005). DD = developmental dyslexia. PLQ = psycholinguistic quotient.
sequences were continuously repeated over 15 blocks of 100 trials, except for Block 14, in which the sequences turned to a random order. In the random block, all four stimulus alternatives occurred equally often, but immediate repetitions of stimulus positions were excluded. Feedback about RTs and error rates was provided after each block. A break of 30 s was imposed before the start of the next block.

After completion of the final sequence-learning task (with the FOC or SOC sequence, depending on the counterbalancing), children’s awareness of sequence learning was assessed. A large array of techniques has been developed to measure explicit awareness following SRT performance, such as verbal reports, forced-choice recognition tests, cued generation tasks, and subjective confidence ratings. The sensitivity and specificity of each of these awareness measures is still subject to debate (see, e.g., Shanks & St. John, 1994, for an extensive discussion on this matter). Because we defined implicit learning as learning that occurs unintentionally, with the resulting knowledge being difficult to express, we opted for a postexperimental interview to establish the amount of explicit awareness children possessed about the sequence. The following questions were asked: (a) do you think the order of stimuli was random or regular; (b) if you think the order was regular, write down as much as possible about the sequence that was used in the last task (it was presumed that knowledge about the first sequence was not a sufficiently sensitive awareness measure due to forgetting over the time course of a week).

RESULTS

Sequence-learning sessions

All analyses were carried out on the mean median RTs or mean error rates per block. Erroneous responses as well as responses following an error were excluded from the RT analyses. For the analysis of variance (ANOVA) analyses, Greenhouse-Geisser corrections were used when the assumption of sphericity was not met. To determine speed–accuracy tradeoffs, one-sample t tests were performed on the correlations between RTs and error rates. All correlations proved to be significantly better than or nonsignificantly different from the reference value 0: for FOC and SOC sequence learning, respectively, in the group of dyslexics, \( r = .22, t(27) = 4.90, p < .001 \), and \( r = .09, t(27) = 1.54, p = .13 \); and in the group of controls, \( r = .29, t(27) = 7.01, p < .001 \), and \( r = .18, t(27) = 3.32, p < .01 \). Because none of the correlations was significantly negative, this indicates that speed–accuracy tradeoffs were absent in both groups on both sequence-learning sessions.

Practice effects

Error rates. The mean error rate per sequenced block (all blocks, except for random Block 14) for FOC and SOC sequence learning amounted to, respectively (a) mean = 2.6 \((SD = 0.44)\), and mean = 2.8 \((SD = 0.67)\) in the group of dyslexics, and (b) mean = 2.7 \((SD = 0.33)\), and mean = 2.8 \((SD = 0.36)\) in the group of controls. Because error rates were in complete agreement with RTs, they were not analyzed further.

RTs. To determine general practice effects or a decrease in RTs over sequenced blocks, we carried out a 2 × 2 × 14 ANOVA with group (dyslexics vs. controls) as between-subjects factor and sequence (FOC vs. SOC) and block (all sequenced blocks) as within-subjects factors. This analysis demonstrated a significant main effect of sequence, \( F(1, 54) = 19.23, MSE = 36,005, p < .001 \), indicating that participants’ overall RT level was higher for FOC learning than for SOC learning, see Figure 1.

A significant main effect of block showed that RTs decreased progressively over sequenced blocks, \( F(5.17, 279.27) = 4.335, MSE = 1,961, p < .001 \). This shows that general RT reductions over blocks were more pronounced in controls than in dyslexics. However, this effect can likely not be accounted for by a superior practice effect in controls. As shown in Figure 1, dyslexics’ initial RT levels were actually lower than those of controls (up to Block 5), \( F(1, 54) = 4.19, MSE = 43,285, p < .05 \), although their RTs leveled out over blocks, as indicated by a nonsignificant main effect of group, \( F < 1 \). Dyslexics’ enhanced initial RT level possibly allowed for less RT gain over the subsequent sequenced blocks. This might explain why RTs reduced faster over sequenced blocks in the group of controls. Remaining main and interaction effects were not significant, \( F < 1 \).

Sequence-learning effects

To estimate sequence-learning effects, we determined the increase in errors/RTs in random Block 14 as compared to the mean of the RTs of the surrounding sequenced Blocks 13 and 15.

![Figure 1. Mean median reaction times (RTs) per block for dyslexic and control first-order conditional (FOC) and second-order conditional (SOC) sequence-learning sessions. All blocks were sequenced, except for random Block 14.](image-url)
Error rates. A $2 \times 2 \times 2$ ANOVA on the mean error rates was performed with group (dyslexics vs. controls) as between-subjects factor and sequence (FOC vs. SOC) and sequence learning (the mean of Blocks 13 and 15 vs. random Block 14) as within-subjects factors. The main effect of sequence learning showed that errors increased significantly in the random block as compared to the surrounding sequenced blocks, $F(1, 54) = 101.05, MSE = 3.04, p < .001$. The Group $\times$ Sequence Learning interaction and the Group $\times$ Sequence $\times$ Sequence Learning interaction, however, were not statistically reliable, both $F < 1$. For FOC and SOC sequence-learning tasks, the sequence-specific learning effects as derived from the interaction, however, were not statistically reliable, both $F < 1$.

RTs. A $2 \times 2 \times 2$ ANOVA was carried out with group (dyslexics vs. controls) as between-subjects factor and sequence (FOC vs. SOC) and sequence learning (the mean of Blocks 13 and 15 vs. random Block 14) as within-subjects factors. A main effect of sequence indicated that the RT level was higher for FOC learning than for SOC learning, $F(1, 54) = 26.34, MSE = 2.256, p < .001$. The main effect of sequence learning also proved to be significant, showing that RTs increased in the random block as compared to the surrounding sequenced blocks, $F(1, 54) = 383.48, MSE = 1.677, p < .001$, see Figure 2.

A significant Sequence $\times$ Sequence Learning interaction further revealed that SOC sequence learning in both groups was better than FOC sequence learning, $F(1, 54) = 4.69, MSE = 1.956, p < .05$. This effect was unexpected, since we predicted better learning of first-order transitions in the FOC sequence than second-order transitions in the SOC sequence. Critically, no interaction of Group $\times$ Sequence Learning, nor an interaction of Group $\times$ Sequence $\times$ Sequence Learning could be observed, both $F < 1$. This shows that sequence learning was highly comparable in both groups: For FOC and SOC sequence learning the sequence-specific learning effects amounted to (a) mean = 89 ms ($SD = 84$), and mean = 121 ms ($SD = 51$) in the group of dyslexics, and (b) mean = 99 ms ($SD = 49$), and mean = 119 ms ($SD = 48$) in the group of controls.

Statistical learning

Sequence learning as assessed by the difference between sequenced and random blocks does not allow disentangling the different types of statistical knowledge. Moreover, because random and sequenced blocks were structurally different, RTs are likely inflated in the random block.$^1$ This might be especially problematic for the assessment of second-order learning in the SOC sequence-learning tasks, because such second-order transitions are less likely to be encountered in the random block. For these reasons, we separated learning of first-order transitions in the FOC sequence from learning of second-order transitions in the FOC and SOC sequences. Determining learning of each type of transition was achieved by comparing median RTs of each type of transition presented in the random block (Block 14) that also occurred in the sequence (trained transitions) with the median RTs of analogous transitions in the random block that never occurred in the sequence (untrained transitions). If participants have acquired knowledge about particular types of transitions, RTs should be faster for trained than for untrained transitions. Accordingly, the analysis of the trained versus untrained transitions in the random block provides a more stringent measure of sequence learning.

First-order learning. This analysis is only relevant for FOC sequence learning, since the SOC sequence contained no predictive first-order information. To determine learning of the specific probability of the first-order transitions, a $2 \times 3$ ANOVA with group (dyslexics vs. controls) as between-subjects factor and training (first-order transitions of probability .67, first-order transitions of probability .33, and untrained first-order transitions) as within-subject factor was carried out. This analysis demonstrated a main effect of training, $F(2, 108) = 91.45, MSE = 1.474, p < .001$. The main effect of group and the Group $\times$ Training interaction were not significant, $F < 1$. Bonferroni post hoc test revealed that first-order transitions with a high probability of .67 were better learned ($M = 418$ ms for dyslexics and $M = 419$ ms for controls) than first-order transitions with a low probability of .33 ($M = 453$ ms for dyslexics and $M = 447$ ms for controls), while both were better learned than untrained first-order transitions ($M = 516$ ms for dyslexics and $M = 513$ for controls), all $p < .05$. Accordingly,

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$^1$We thank Iring Koch and an anonymous reviewer for pointing out this concern.
this analysis indicates that dyslexic and control children became equally sensitive to the predictive information held in the first-order transitions of the FOC sequence.

**Second-order learning.** To determine second-order learning of the FOC and SOC sequences, we first isolated all first-order transitions presented in the random block that occurred in the sequence (such as 13 in the FOC sequence). These first-order transitions were subsequently divided into (a) first-order transitions with a preceding sequence element making up second-order transitions that occurred in the sequence (called trained second-order transitions, such as 213 in the FOC sequence) and (b) first-order transitions with a predecessor not occurring in the sequence (called untrained second-order transitions, such as 413 in the FOC sequence). Because both types of transition are inferred from first-order transitions, the comparison of trained against untrained second-order transitions reflects a measure of second-order learning without incorporating first-order learning. A $2 \times 2 \times 2$ ANOVA was carried out with group (dyslexics vs. controls) as between-subjects factor and sequence (FOC vs. SOC) and training (trained vs. untrained second-order transitions) as within-subjects factors. This analysis showed a main effect of training, $F(1, 54) = 134.43$, $MSE = 639$, $p < .001$, with trained transitions being faster than untrained transitions in both dyslexics ($M = 442$ ms vs. $M = 470$ ms for second-order FOC transitions and $M = 404$ ms vs. $M = 459$ ms for second-order SOC transitions) and controls ($M = 439$ ms vs. $M = 460$ ms for second-order FOC transitions and $M = 409$ ms vs. $M = 461$ ms for second-order SOC transitions). There was also a significant Sequence $\times$ Training interaction effect, indicating that learning of second-order transitions was more pronounced for the SOC sequence than for the FOC sequence, $F(1, 54) = 15.99$, $MSE = 736$, $p < .001$. This effect was expected, since it was predicted that learning of the FOC sequence would already be accomplished on the basis of less complex first-order transitions. Importantly, the main effect of group, the Group $\times$ Training interaction, and the Group $\times$ Sequence $\times$ Training interaction were not significant. This demonstrates that second-order learning was highly similar in both groups.

**Differences in learning in function of type of transition.**

In order to compare the amounts of first- and second-order learning, we calculated a difference score between untrained and trained transitions for each type of transition in function of each type of sequence (FOC or SOC). The difference scores for first-order FOC, second-order FOC, and second-order SOC transitions in both groups are displayed in Figure 3.

A $2 \times 3$ ANOVA was carried out on the difference scores with group (dyslexics vs. controls) as between-subjects factor and sequence (FOC vs. SOC) and type of transition (first-order FOC, second-order FOC, and second-order SOC) as within-subjects factors. This analysis revealed a significant effect of type of transition, $F(2, 108) = 22.11$, $MSE = 1,549$, $p < .001$. Other effects were not significant, $F < 1$. Bonferroni post hoc tests showed that learning of first-order transitions of the FOC sequence was better than learning of second-order transitions of the SOC sequence, while both types of learning were better than learning of second-order transitions of the FOC sequence, all $p < .05$. These results are in line with the expectations that second-order information would be more difficult to acquire than first-order information.

Second-order learning effects derived from the difference between trained and untrained transitions are smaller than the ones obtained from contrasting random and surrounding sequenced blocks in the SOC sequence-learning task (see the subsection “Sequence-Learning Effects” in the Results section). Note that the superior SOC learning effect established in the previous analysis of sequence learning (see the subsection “Sequence-Learning Effects” in the Results section) also disappeared using a more stringent test of sequence learning. This shows that sequence-learning effects derived from structurally different blocks (random vs. sequenced blocks) should be interpreted with caution.

In sum, the analyses of statistical learning revealed that learning of first-order transitions in the FOC sequence was more pronounced than learning of second-order transitions in the FOC and SOC sequences. Moreover, the results confirm that sequence-learning effects were highly similar in the dyslexic and control groups.

**Power analyses**

To rule out that the observed null-effects in sequence learning were due to a lack of statistical power, we carried out post hoc power analyses on the median RTs using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007). The analyses are relevant for both measures of sequence learning: (a) the difference between the random and adjacent sequenced blocks (2 repetitions, Block 14...
versus mean of Blocks 13 and 15), and (b) the difference between trained and untrained transitions (2 repetitions). The power analyses showed that for a statistical $F$-test, type repeated measures within-between interaction, with $\alpha = .05$, total sample size = 56, 2 groups, and 2 repetitions, the power ($1 - \beta$) to detect a small ($f = .10$), medium ($f = .25$), and large effect ($f = .40$) amounted to, respectively, .31, .96, and .99. Because severe learning deficits in dyslexia are unlikely to be manifested as very small effects, this suggests that statistical power in the present study was fairly good.

**Explicit sequence awareness**

Except for 2 children in the dyslexic group and 3 children in the control group, all children (91%) believed that the sequence of stimuli was regular after having performed two learning sessions. An explicit awareness score was determined for each participant based on the number of correctly reproduced consecutive elements of the last sequence divided by the total number of 12 sequence elements (ranging from 0 when no element could be reproduced to 1 when reproduction was perfect). The awareness score for the FOC and SOC sequence amounted to, respectively, (a) mean = 0.13 ($SD = 0.16$), and mean = 0.13 ($SD = 0.14$) in the group of dyslexics, and (b) mean = 0.15 ($SD = 0.13$), and mean = 0.22 ($SD = 0.30$) in the group of controls. This indicates that, on average, not more than two consecutive elements could be reproduced correctly. Only 1 (control) child was able to correctly recall 10 out of 12 consecutive sequence elements.

To determine differences in awareness, a $2 \times 2$ ANOVA with group (dyslexics vs. controls) and sequence (FOC vs. SOC) as between-subjects factors was carried out on the explicit awareness score. This analysis revealed that explicit awareness did not differ between the two groups, $F(1, 52) = 1.13$, $MSE = 0.04$, ns, nor between the two sequence-learning tasks, $F < 1$. The Group × Sequence interaction was also not significant, $F < 1$. This shows that the amount of sequence awareness was comparable for both groups and sequences.

In conclusion, the analyses of awareness suggest that, although most dyslexic and control children noticed some regularity in the task, none of them were able to accurately describe the knowledge they possessed. This indicates that learning in both groups was primarily governed by implicit processes.

**Influence of age, literacy, and education on sequence learning**

In order to determine the stability of sequence-learning performance in DD, we carried out correlational analyses of age effects on sequence learning for the group of dyslexics. None of the correlations between age and sequence learning, however, proved to be reliable: For FOC and SOC sequence learning the correlation amounted to, respectively, $r = .01$ and $r = -.23$, both ns. This suggests that sequence-learning performance remains comparable within this age group, despite the larger age range from 12 to 15 years. Furthermore, because we found no indication for a sequence-learning deficit in dyslexia, we exploratively examined the influence of literacy and education on the amount of sequence learning in the group of dyslexics. No significant correlation could be established between sequence learning and reading or writing abilities as derived from the PLQ of the DST in the group of dyslexics: For FOC and SOC sequence learning, respectively, the correlation amounted to $r = -.15$ and $r = -.28$, both ns. Finally, we failed to observe a significant correlation between education and sequence learning in the group of dyslexics: For FOC and SOC sequence learning the correlation amounted to, respectively, Kendall’s $\tau = .16$ and $\tau = -.05$, both ns.

**GENERAL DISCUSSION**

In the present study, we investigated the influence of structural complexity on implicit sequence learning in secondary-school-aged children with developmental dyslexia (DD). Previous studies reported mixed results, with some authors observing impaired sequence learning in dyslexic children (Vicarei et al., 2005) and adults (Howard et al., 2006; Menghini et al., 2006; Stoddley et al., 2006) and others finding intact sequence learning in adult dyslexics (Kelly et al., 2002; Rüsseler et al., 2006). One of the factors that are known to have a large impact on sequence learning is the complexity of the statistical information that can be acquired during learning. In none of the studies on DD, however, were the statistical characteristics of the sequences taken into account.

The purpose of our study was therefore to investigate the influence of statistical complexity on sequence learning in dyslexia by directly comparing first-order and second-order learning. The current sample consisted of children between 12 and 15 years. This age has not yet been examined in prior research, making it interesting to determine whether sequence-learning performance in DD evolves with age. Contrary to previous findings of attenuated sequence learning in dyslexia, we observed no differences in sequence learning between the dyslexic and control children. Learning of first-order transitions and second-order transitions was highly similar in both groups. This indicates that differences in statistical complexity likely cannot account for the mixed reports of sequence-learning performance in DD. The observation that second-order learning was intact is also in disagreement with the suggestion of Howard et al. (2006) that dyslexics have a specific impairment of implicit learning of higher order transitions. Sequence learning of higher order transitions has been associated with medial temporal lobe (MTL) structures, suggested to be responsible for the binding of temporally or spatially separated events (e.g., Curran, 1997; Fletcher et al., 2005; Schendan, Searl, Melrose, & Stern, 2003). Abnormalities in MTL structures, however, are not known to be characteristic of dyslexia. The current results also suggest that this function is preserved in dyslexia.
In our study, we included more girls than boys. This might seem atypical given the higher prevalence of DD in boys. It should be noted that all of the dyslexic children were clinically diagnosed as having DD, so gender was not expected to affect performance. Nevertheless, to rule out gender-related differences in performance in DD, additional factorial ANOVAs were run with group (dyslexics vs. controls) and gender (male vs. female) as between-subject factors on all administered literacy and working memory tests of the DST. The same was done for sequence-learning effects (as derived from an increase in RTs in random compared to adjacent blocks) and statistical learning of each type of transition (first-order FOC, second-order FOC, and second-order SOC). None of the reported differences in literacy skill between dyslexics and controls proved to be affected by gender (the Group × Gender interactions were not reliable). Sequence-learning effects and statistical learning were also unrelated to gender (none of the Group × Gender interactions was significant). This suggests that the results of the present study are not gender-specific, and therefore the composition of the used sample cannot account for the reported null-effects.

Like in previous studies of sequence learning in dyslexia, all children had to carry out the SRT task using (two fingers of) both hands. Because it has been shown that the representational nature of sequence knowledge varies as a function of the specific effector used (e.g., Berner & Hoffmann, 2008; Deroost, Zeeuws, & Soetens, 2006), the two-hand procedure was preserved to allow comparison across studies of sequence learning in DD. It is interesting to note that despite accruing evidence for a less developed corpus callosum structure in dyslexia (e.g., von Plessen et al., 2002) dyslexic children experienced no difficulties in executing the SRT task with both hands.

According to our knowledge, this study is the first in reporting intact sequence learning in dyslexic children. Dyslexics’ initial level of performance (RTs) even exceeded those of controls. This finding could not be attributed to speed–accuracy tradeoffs and is therefore in disagreement with previous studies observing reduced speed of processing in choice (but not simple) reaction time tasks in dyslexic children (e.g., Nicolson & Fawcett, 1994). However, it should be noted that impairments in speed of processing are not consistently observed in choice reaction time tasks in dyslexic children (e.g., Snowling, 2006). Hence, this suggests that impairments in speed of processing are not fully developed compensation strategies. This is quite remarkable, given the fact that all children carried out two sequence-learning sessions (it remains to be determined whether possible proactive interference effects can account for this finding). The amount of awareness did also not differ between the two groups. Hence, this suggests that sequence-learning performance in all children was primarily governed by implicit processes. Likely, this is due to the rather complex and lengthy nature of the sequence structures and the use of a very short response–stimulus interval (RSI) of 50 ms. Both factors are known to hamper the development of explicit awareness (e.g., Destrebecqz & Cleeremans, 2001). In contrast, those studies that reported sequence-learning deficits consistently made use of rather short, predictive sequence structures, which are prone to stimulate the development of explicit knowledge, and longer RSIs. It is interesting to note that Rüsseler et al. (2006) also failed to observe any sequence-learning impairment in adult dyslexics with a 12-stimuli SOC sequence (132434123142), comparable to the one used in the present study.

Accordingly, the differential findings between the present study and previous reports of learning deficits suggest that explicit sequence learning may be disrupted in DD, whereas implicit learning is (largely) unaffected. Awareness of sequence learning has been specifically associated with prefrontal functioning (e.g., Destrebecqz et al., 2003; Destrebecqz et al., 2005; Grafton, Hazeltine, & Ivry, 1995; Pascual-Leone, Wassermann, Grafman, & Hallett, 1996; Robertson & Pascual-Leone, 2003). The prefrontal cortex is the key structure for executive control and working memory, indispensable for literacy skill. Dyslexics have been shown to display greater amounts of Stroop interference (Everatt, Warner, & Miles, 1997; Helland & Asbjørnsen, 2000; Protopapas, Archonti, & Skaloulambakas, 2007), as well as impaired performance on various executive and working memory...
tests (Brosnan et al., 2002; Helland & Asbjørnsen, 2000; Poblano, Valadez-Tepc, de Lourdes Arias, & García-Pedroza, 2000; Reiter, Tucha, & Lange, 2005). In the present study, dyslexics also performed more poorly on working memory tasks of the DST (Phonemic Segmentation and Backwards Digit Span) than did controls. Taken together, this could point toward some prefrontal malfunction in DD (Vasic, Lohr, Steinbrink, Martin, & Wolf, 2008).

Interestingly, the dyslexic automatization hypothesis of Nicolson and Fawcett (1990) is also largely based on observations of reduced dual-task performance on gross motor skill tasks. Dual-task performance, or the ability to simultaneously coordinate two tasks, is known to heavily rely on prefrontal functioning. Consequently, it is possible that the deficient explicit sequence learning is part of a broader deficit associated with impairments of prefrontal regions or prefrontal-cerebellar connections in DD. At present, this explanation warrants further investigation. The present study was not aimed at attributing to the explicit/implicit sequence-learning debate. Therefore, explicit sequence learning was only assessed post hoc after SRT performance and not rigorously controlled for. In order to determine whether explicit learning and related prefrontal abnormal functioning can truly account for the sequence-learning deficits in DD, one could contrast learning of fixed deterministic sequences with learning of probabilistic sequences, known to be less facilitated by explicit awareness. Another possibility is to compare the performance of intentional, explicit learners who memorize the sequence before carrying out the SRT task with incidental, implicit learners, who remain uninformed about the sequential nature of the task.

To further clarify the role of prefrontal functioning and dual tasking in sequence learning in DD, implicit and explicit sequence learning under standard single-task conditions should be compared with learning under conditions of additional working memory load (tone-counting; for a review, see Shanks, 2003). Using a factorial design crossing implicit/explicit and single/dual-task factors will allow determination of the respective contribution of each of these aspects to dyslexics’ sequence-learning performance. This will enhance our understanding of prefrontal functioning in DD.

In conclusion, in the present study, we found no evidence for attenuated implicit sequence learning in dyslexia. Children between the ages of 12 and 15 years performed equally as well as matched controls on first-order and second-order sequence learning. This suggests that mixed reports of sequence-learning performance in DD cannot be attributed to differences in statistical complexity of the sequences. A possible explanation for the divergent evidence might be that sequence learning in the present study was preserved due to its predominantly implicit nature, whereas explicit sequence learning was disturbed in previous studies on dyslexia. This suggests that impairments in skill automatization, as proposed by Nicolson and Fawcett (1990), are not general in nature, but depend on the type of task used. If the implicit part of skill automatization is indeed intact in dyslexia, it might be advisable for schools to focus on implicit rather than explicit learning strategies when dyslexic children start developing literacy skill. More research directly comparing explicit and implicit learning processes is necessary to clarify this issue.

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