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Author(s): Gracia Jiménez-Fernández, Joaquín M. M. Vaquero, Luis Jiménez and Sylvia Defior
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Dyslexic children show deficits in implicit sequence learning, but not in explicit sequence learning or contextual cueing

**Gracia Jiménez-Fernández • Joaquín M. M. Vaquero •
Luis Jiménez • Sylvia Defior**

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Abstract Dyslexia is a specific learning disability characterized by difficulties with accurate and/or fluent word recognition and by poor spelling abilities. The absence of other high level cognitive deficits in the dyslexic population has led some authors to propose that non-strategical processes like implicit learning could be impaired in this population. Most studies have addressed this issue by using sequence learning tasks, but so far the results have not been conclusive. We test this hypothesis by comparing the performance of dyslexic children and good readers in both implicit and explicit versions of the sequence learning task, as well as in another implicit learning task not involving sequential information. The results showed that dyslexic children failed to learn the sequence when they were not informed about its presence (implicit condition). In contrast, they learned without significant differences in relation to the good readers group when they were encouraged to discover the sequence and to use it in order to improve their performance (explicit condition). Moreover, we observed that this implicit learning deficit was not extended to other forms of non-sequential, implicit learning such as contextual cueing. In this case, both groups showed similar implicit learning about the information provided by the visual context. These results help to clarify previous contradictory data, and they are discussed in relation to how the implicit sequence learning deficit could contribute to the understanding of dyslexia.

Keywords Automatization · Dyslexia · Intentional learning · Reading disabilities · Unconscious learning

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G. Jiménez-Fernández · S. Defior
Departamento de Psicología Evolutiva y de la Educación, Universidad de Granada, Granada, Spain

J. M. M. Vaquero (✉)
Departamento de Psicología Experimental y Fisiología del Comportamiento, Facultad de Psicología, Universidad de Granada, Campus Universitario Cartuja s/n, 18071 Granada, Spain
e-mail: joaquinm@ugr.es

L. Jiménez
Departamento de Psicología Social, Básica y Metodología, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

Dyslexia is a specific learning disability characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities in spite of provision of regular classroom instruction and in the absence of other cognitive disabilities or general intelligence deficit. Secondary consequences may include problems in general reading comprehension and reduced reading experience, which can impede the growth of vocabulary and background knowledge (International Dyslexia Association (IDA). Board of Directors, 2002; Lyon, Shaywitz & Shaywitz, 2003). The absence of an intelligence deficit or other cognitive disabilities has led some authors to suggest that reading and writing problems may lie not so much in learning processes driven by conscious strategies but rather in implicit learning processes also involved in learning to read (Gombert, 2003; Pacton, Perruchet, Fayol & Cleeremans, 2001; Sperling, Lu & Manis, 2004; Steffler, 2001).

Implicit learning is typically defined as the acquisition of knowledge that takes place regardless of conscious attempts to learn and in such a way that the resulting knowledge is difficult to express (Berry & Dienes, 1993; Reber, 1993). Because sequence learning is considered to be inherent to the acquisition of reading and writing skills, the hypothesis of an implicit learning deficit in dyslexia has often been tested using sequence learning tasks. In the typical sequence learning paradigm, first developed by Nissen & Bullemer (1987), several locations are marked on a computer screen and one stimulus appears on each trial in one of these locations. Participants are instructed to respond to each trial as fast and accurately as possible by pressing a key spatially consistent with the current location of the stimulus. Unknown to the participants, the successive locations of the stimulus follow a sequence that is repeated consistently over each practice block. Participants become progressively sensitive to this pattern, as attested by the fact that responses are slowed down when the stimulus stops following that sequence. This performance pattern shows that participants learn to predict a series of locations without being instructed to do so and arguably without becoming aware of the contents of learning. To assess this question, researchers have compared the sequence learning expressed through the reaction time (RT) measure (indirect measure) with that manifested through recognition or generation tasks (direct measures), in which participants are explicitly asked to use whatever relevant knowledge they may have about the sequence to either generate or recognize sequential fragments (Jiménez, Méndez & Cleeremans, 1996; Perruchet & Amorim, 1992; Shanks & St. John, 1994). Many studies have obtained evidence of sequence learning through measures of RT without comparable levels of explicit knowledge as measured by recognition and generation tasks, thus making sequence learning one of the best paradigms through which to study implicit learning (Destrebecqz & Cleeremans, 2001).

Several recent studies have observed a deficit in sequence learning in both children (Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari & Petrosini, 2003) and adults with dyslexia (Howard, Howard, Japikse & Eden, 2006; Stoodley, Harrison & Stein, 2006; Menghini, Hagberg, Caltagirone, Petrosini & Vicari, 2006). Yet, this evidence is not conclusive, since other studies have failed to obtain such a deficit in children (Menghini et al., 2010; Waber et al., 2003) and adults (Kelly, Griffiths & Frith, 2002; Rüsseler, Gerth & Münte, 2006). Variations in the specific procedures employed in these studies may account for a number of these inconsistencies. A first major difference between the sequences used in different studies lies in the frequency of each type of event (for example, locations) within a given sequence. Sequences have been sometimes selected without balancing the frequency of each event (e.g., Menghini et al., 2006; Stoodley et al., 2006; Vicari et al., 2005), which may lead participants to respond based on the frequency of each stimulus rather than on the sequential structure (Reed & Johnson, 1994). A second major difference between studies producing contradictory results in dyslexic people lies in the relative complexity of the sequences. Some studies have used first-order sequences (e.g., Vicari et al., 2003), in which the location of the target stimulus can be predicted easily by knowing the location of just the previous stimulus, whereas other studies arranged more complex, second-order structures, in which predicting the location of a stimulus requires maintaining information about at least the two previous locations (e.g., Rüsseler et al., 2006; Waber et al., 2003). This difference in complexity is particularly important, since first-order sequences are easier to discover and to rehearse deliberately, thus meaning that any possible pattern of results between dyslexic and control groups could not be univocally interpreted as showing either a difference or an equivalence between them concerning implicit learning processes but rather a difference or equivalence on some particular mixture of implicit and/or explicit learning effects.

Taking these differences between studies into account, it would be important to explain why some studies have obtained equivalent learning effects in dyslexic and control groups, whereas some others have found implicit learning deficits in dyslexia. Unfortunately, the methods have often made it impossible to assess sequence learning separately from other, non-learning effects. Specifically, in all the studies mentioned, above sequence learning has been assessed by introducing a control block in which the sequence was replaced by random trials. The increase in RT due to the change of the sequential pattern is considered as the index of learning. However, using random locations can lead to increases in RT not necessarily related to sequence learning (Reed & Johnson, 1994; Vaquero, Jiménez & Lupiáñez, 2006). It has been found, for instance, that alternating locations (such as in 2-3-2) produces slower RT than does responding to non-alternating trials (Vaquero et al., 2006). In practice, alternating trials have been usually avoided from the training sequences because they are thought to result in highly salient fragments, which could be easily discovered by participants. As a consequence, random blocks usually contain more reversals that do sequential trials and therefore produce slower average RT even before participants have started to learn the sequence (Vaquero et al., 2006).

So far, all the studies that have assessed sequence learning with a dyslexic population have been affected by one or more of these methodological issues. For instance, Waber et al. (2003) used a second-order conditional (SOC) sequence in which three possible locations were presented with equal frequency (3-1-2-1-3-2) but the sequence contained fewer reversals than those expected by chance. After four training blocks, a control block with random locations was presented, resulting in an increase in RT which was equivalent to that found in a control group of non-dyslexic children. This result was interpreted as evidence that both groups learned the sequence to the same extent and hence that there was no evidence of an implicit learning deficit in dyslexia. However, an equally plausible account for these results could be taken by assuming that learning about such a relatively complex, second-order sequential structure could be negligible after only four training blocks and that most of the increase in RT observed at that point over the control block could be due to the increased amount of reversals produced over the random block. Given that there was no reason to expect a difference between good and poor readers regarding the effect of reversals, a similar increase in RTs should be found in both groups.

In order to provide new evidence to clarify whether there is a deficit in implicit learning in dyslexic children, we carried out a series of three experiments. Experiment 1 was aimed to find out whether results which contradict with the hypothesis that dyslexic children show a deficit in implicit learning, such as those reported by Waber et al. (2003), may have been affected by artifacts such as the number of reversals. To avoid this artifact, instead of using a random block to assess learning about a second-order conditional sequence, we used two balanced sequences, one for the training blocks and one for the control block. These two

SOC sequences (i.e., training and control) had a homogeneous structure in which each single event, each legal transition between events, and the overall proportion of reversals were equally probable, meaning that these factors did not change between training and control blocks. After controlling these procedural aspects, we were in a better position to assess implicit sequence learning in dyslexic and control samples.

In experiment 2, implicit and intentional (explicit) sequence learning was explored to verify the extent to which any observed deficit obeys either to an automatic process of accrual of sequence information or to a more deliberative mechanism of search for regularities. In experiment 2a, an implicit sequence learning task was used to compare dyslexic children with a control group of good readers. In experiment 2b, the same participants were provided with instructions which revealed the existence of a sequence (different from the sequence in experiment 2a), and they were encouraged to try to learn this sequence in order to improve their performance. Thus, we compared the results arising in an implicit learning task with those found in an intentional version of the same learning task. The results of this experiment may help us to understand the results of several previous studies which have arranged fairly simple sequences and which could have ended up producing the explicit recognition of the sequences as a result of their repeated presentation, even though the learners were not deliberately oriented toward an explicit search for regularities.

Finally, in experiment 3, we assessed whether dyslexic children might also show deficits in non-sequential implicit learning tasks. As mentioned above, there are only a few studies investigating implicit learning in dyslexia using tasks other than that of sequence learning. These few studies have been carried out exclusively with adult populations, and they have not observed deficits (Howard et al., 2006; Pothos & Kirk, 2004; Rüsseler et al., 2006). For example, Howard et al. (2006) showed that a sample of dyslexic adults had a deficit in sequence learning but not in a contextual cueing task, which involves using an informative context to constrain the search for a simultaneous target (Chun & Jiang, 1998). In this task, participants are told to look for and to respond to the identity of a target which is embedded in a complex visual display. On a fraction of these trials, the configuration of distractors conveys relevant information about the location of the target, and it has been observed that participants become sensitive to this contextual information, thus responding faster to these repeated configurations, as compared to those trials in which the context is not informative. Improvement in responding to repeated contexts indicates contextual learning, and it is often not accompanied by awareness of the relation between repeated contexts and the location of the target. Thus, this task is currently considered as one of the most robust paradigms of implicit learning. In the present study, we adapted a variant of the contextual cueing task in order to explore whether this form of learning is preserved in dyslexic children or whether, on the contrary, the results found in dyslexic adults might have been caused by the development of some compensatory strategies. Recent studies using other implicit learning paradigms (namely, the artificial grammar learning task) have obtained contradictory results. For instance, Pothos & Kirk (2004) and Rüsseler et al. (2006) found that dyslexic adults did not show any deficit in this task, but Pavlidou, Williams & Kelly (2009) reported a failure to obtain learning in a group of dyslexic children when using this task. Artificial grammar learning involves some sequential content, so that this form of learning may share part of the learning system recruited for sequence learning. In contrast, contextual cueing does not involve any kind of sequential constraint, and thus, our prediction is that contextual cueing learning would be preserved in a group of dyslexic children.

The criteria used to classify participants as dyslexics also constitute another major difference among studies, which may have contributed to obtain inconsistent results. Some studies have used word and pseudoword reading tests to assess, respectively, the lexical and phonological routes of reading (e.g., Howard et al., 2006; Rüsseler et al., 2006). Yet, other studies have used only a word reading test (e.g., Kelly et al., 2002; Stoodley et al., 2006; Waber et al., 2003) or even have included a group diagnosed with dyslexia without further specifying which assessment tests were used (Vicari et al., 2003, 2005). In the present study, participants were selected using the common procedure to assess dyslexia in a transparent orthography. In Spanish, this involves using a standard battery (Test de Lectura y Escritura en Español, LEE; Defior et al., 2006) that assesses both the lexical and phonological routes, taking into account both reading accuracy and speed (the latter being a very important measure in a transparent orthography). In addition, all the experiments we conducted with children because we aimed to ensure that no compensatory strategies could have been developed to overshadow a deficit in implicit learning.

Experiment 1: improving sequence learning assessment over the control block

The objective of this experiment was to conceptually replicate with non-dyslexic children the procedure of Waber et al. (2003), in which the authors used a SOC sequence but assessed learning by introducing a random block. Training participants with a SOC sequence minimizes the chances that they may discover and use the training sequence consciously. However, instead of testing learning by introducing a random block as Waber et al. did, we presented an analogous, non-trained sequence over the control block in order to control for the frequency of reversals. The sequences were actually taken from Cohen, Ivry & Keele (1990), and they were 3-1-2-1-3-2 (training) and 3-2-1-2-3-1 (control). As can be observed, both sequences are statistically analogous, with the only difference being that locations 1 and 2 are exchanged. Hence, the frequency of each location was balanced and so was the proportion of reversals between training and control blocks. In others words, using an analogous control sequence instead of a set of random trials will ensure that these control block do not introduce artifacts which could unduly pass as an effect of sequence learning.

In the study by Waber et al. (2003), the increase in RT caused by the introduction of a random block after only four training blocks was interpreted as evidence of sequence learning. If the present experiment does not show a similar increase in RT after the introduction of an untrained sequence, this would tend to support the alternative conclusion that the increase could have been caused by a non-learning artifact (for example, that the increase in RT was due to the increase in the proportion of reversals in the random block). We will also confirm that responding to reversals results in a significant slowing of performance even before training.

Method

Participants

The sample was composed of 16 children of ages ranging from 8 to 9 years. Candidates were selected to have average intelligence (IQ 90–110, RAVEN; see "Materials") and their reading age matched their chronological age (as assessed by the *Prueba de Evaluación del Retraso Lector* (PEREL); see "Materials"). All participants were in the school year corresponding to their chronological age and had never participated in a similar study before.

Materials

Intellectual capacity was estimated using the CPM version of the RAVEN test (Raven, 1995). Reading age was estimated by applying the PEREL (Test for Backward Reading Assessment; Soto, Sebastián & Maldonado, 1992). This is a standardized test used to obtain an index of reading skills in Spanish population. It includes 100 words of different frequency ordered according to their length and complexity. The test provides two scores: decoding, measured by the number of words in which participants apply the grapheme-to-phoneme correspondences rules properly; and reading, where not only proper decoding is taken into account but also fluency—understood as fast and accurate reading following the proper stress patterns. The reading score is used to obtain the reading age. The objective was to assess reading age in order to select children whose reading age matched their chronological age. Cronbach's alpha reliability coefficient is 0.82 and criterion-related validity is 0.67. Therefore, no specific tests were used to assess the lexical route and the phonological (sublexical) route in this experiment. Such tests were used when the objective was to select (and compare) dyslexic children and typically developing children (experiments 2 and 3).

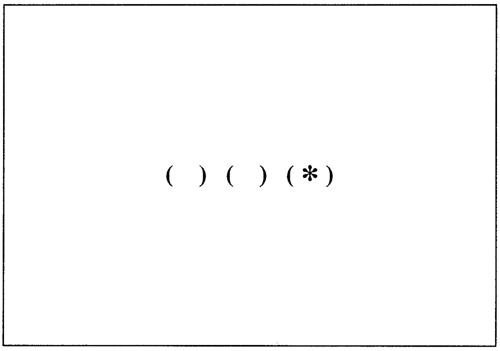
Apparatus

The sequence task was programmed using E-PRIME software version 1.2 (Schneider, Eschmann & Zuccolotto, 2002) running on a Pentium 4 laptop computer. Participants responded by pressing one of three possible keys on the keyboard.

Procedure

This task reproduced the display used by Waber et al. (2003). Three locations were shown on the horizontal axis of the screen by means of three pairs of brackets. In each trial, a letter X appeared in one of the three locations (see Fig. 1). Participants had to press the key that corresponded to the location of the letter X as fast and accurately as possible. Response keys were B-N-M on the Spanish keyboard; they had spatial correspondence with the three possible locations of the stimulus on each trial. Thus, participants were instructed to press B when the stimulus appeared in the leftmost location, N when it appeared in the central location, and M when it appeared in the rightmost location. The brackets remained on the screen during the whole task. The distance between the centers of the brackets was 2.5 cm. Children remained seated in front of the computer at an

Fig. 1 Example of a trial taken from experiments 1 and 2a. In experiment 1, the stimulus was the letter X instead of *one asterisk*



approximate distance of 40 cm and were told to keep the index, middle, and ring fingers of their right hand on the B-N-M keys.

The task comprised eight blocks of 60 trials each (see Table 1). The first block was composed of 60 practice trials in which the locations of the stimulus were random with the only constraint of avoiding repetitions of the same location in two consecutive trials. This unstructured block allowed us to assess the effect of reversals before training with a sequence that contains fewer reversals than expected by chance. The second block was a control block presenting five repetitions of each of the two SOC sequences which were going to be used as the training and control sequences. Both sequences were presented within the same block 2 to verify that they were responded to with similar RTs by participants with no previous experience with any of them. If this was confirmed, then the increase in RT expected over the control block, when the training sequence was replaced by the control one, could only be interpreted as an index of sequence learning. The training sequence was actually the one used by Waber et al. (2003), 3-1-2-1-3-2, whereas the control sequence was 1-3-2-1-2-3. Over the control block 2, the order of presentation of the five cycles of each of the two sequences was random. The two sequences started from the same point, so as to control that each cycle had exactly two reversals. From block 3 to 6, the training sequence was repeated continuously over series of 60 trials. Block 7 presented another 60 trials in which the control sequence replaced the training one, and finally block 8 reintroduced the training sequence over a final series of 60 trials.

The training and control sequences were not counterbalanced between subjects because the control one included a salient fragment (i.e., the run 1-2-3) which, in pilot studies, had proved to be particularly easy to discover. However, as explained above, the use of a pre-training control block (block 2) in which both sequences were tested simultaneously allowed us to rule out the existence of any difference between sequences before learning. To promote implicit learning of the training sequence, participants were instructed to respond as fast and accurately as possible, and no mention was made of the presence of a sequence.

Results and discussion

In the RT analyses, the first two trials from each block, as well as error responses and outliers, defined as those trials departing more than 3 standard deviations from the specific mean from each participant and block (1.7%), were eliminated from the analyses. Accuracy mean was 93.9%. Throughout all the analyses, the pattern of results shown by the measures

Table 1 Experimental design of experiment 1

Block	Trials	Order
1	60	Random without repetitions
2	60	Presentation of training and control sequences
3	60	Training sequence
4	60	Training sequence
5	60	Training sequence
6	60	Training sequence
7	60	Control sequence
8	60	Training sequence

of accuracy mirrored that found for the measures of RT. Therefore, we focused specifically on the description of the RT results.

Figure 2 shows the mean RTs obtained over the entire experiment. As can be seen, a decrease in RTs was observed over the training blocks; however, RTs did not increase over the control block 7, as it should be expected if participants have learned about the training sequence.

An analysis of block 1, in which locations were random without repetitions, showed that RTs for reversals (737 ms) were significantly higher than RTs for non-reversal trials (638 ms; $F(1, 15)=8.25$, $p=0.012$). The comparison between sequences before learning was undertaken by comparing responding to each sequence in block 2, after removing the first cycle (i.e., the first six trials) which produced extremely slow responses. The analysis of this block showed no significant differences in RTs between both sequences ($F<1$). Sequence learning after training was assessed by comparing RT over the control block 7, with the average RT obtained in its neighboring training blocks 6 and 8. This analysis did not show any significant difference between responding to training and control blocks ($F<1$). Thus, we found no evidence of sequence learning after an amount of training comparable to that used in the study by Waber et al. (2003).

The absence of learning after four training blocks led us to consider the possibility that the increased RTs found in the original experiment by Waber et al. (2003) may have been caused by the increased amount of reversals included over their random block rather than reflecting a genuine effect of sequence learning. Our data from block 1 confirmed that reversals produced slower RT independently of learning. Given that the expected proportion of reversals over a random block without repetitions is 0.5, whereas the actual proportion of reversals within the structured sequences was 0.3, it would be likely that the increase in RT observed by Waber et al. (2003) in both children with poor reading abilities and in their control counterparts might be taken as showing that children with dyslexia are also affected by reversals and not that they can learn implicitly about a sequence to the same extent than did the control group. In order to ascertain more clearly whether there is an implicit sequence learning deficit in dyslexic children, we arranged two new experiments in which larger periods of training were provided to both dyslexic and control groups, in which the effect of reversals was controlled by using statistically analogous sequences for training and control blocks, and in which the explicit vs implicit nature of the resulting knowledge were directly manipulated in two successive experiments.

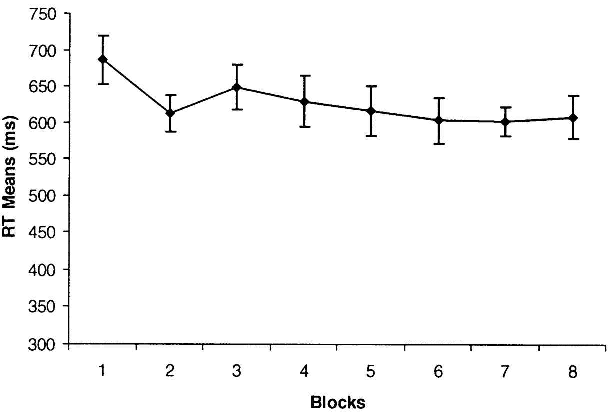


Fig. 2 Mean RT in experiment 1 across blocks of training. *Error bars* represent standard errors of the mean

Experiments 2a and 2b: implicit vs intentional sequence learning

The objective of experiment 2a was to find out whether dyslexic children would show a deficit in implicit sequence learning with a second-order sequence. In contrast, in experiment 2b, participants were informed about the presence of a sequence, and they were instructed to learn it intentionally as a way to improve performance. The same subjects participated in both experiments, with an approximate interval of 1 week between the two experiments. These experiments involved using the same task as in experiment 1 but increasing the number of training blocks: seven for the implicit task and six for the intentional task. Pilot research conducted on normal reading controls had shown that this increase was enough to allow these participants to learn the sequence.

Method

Participants

The sample was composed of 28 children of ages ranging from 8 to 9 years (mean 8 years and 4 months): 14 of which were selected to form the dyslexic group and the other 14 were selected to form the control group. Children in the dyslexic group (nine girls and five boys) had average scores in the RAVEN intelligence test (IQ 90–110), but none of their scores in the four reading tests administered was above the 25th percentile (see Table 2). Children in the control group (nine girls and five boys) had average scores in the intelligence test, and all their scores in the reading tests were equal to or greater than the 65th percentile. All participants were in the school year that corresponded to their chronological age. None of them had ever been diagnosed with dyslexia or any other disorder, and they all participated for the first time in this type of study.

Materials

Intellectual capacity was estimated using the CPM version of the RAVEN test (Raven, 1995). Two tests of reading from the LEE battery (Defior et al., 2006) were used to assess both lexical processes (lexical route) and sublexical processes (phonological route) involved in reading (Coltheart, Curtis, Atkins & Haller, 1993). Such tests were word reading and pseudoword reading. In addition, each test involved two scores: accuracy and speed. Thus, four measures of reading were registered.

Table 2 Participants experiment 2a and 2b

	Male/ female	Age (months)	IQ (RAVEN)	Word reading accuracy (percentile)	Word reading fluency (percentile)	Pseudoword reading accuracy (percentile)	Pseudoword reading fluency (percentile)
Dyslexic children ($n=14$)	5/9	100 (3.27)	100 (7.8)	14.29 (6.16)	19.64 (6.34)	12.14 (4.69)	17.86 (7.26)
Control readers ($n=14$)	5/9	99 (4.32)	102.8 (7.3)	76.78 (10.67)	81.07 (10.41)	80.35 (9.7)	78.93 (9.02)
		n.s.	n.s.	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$

For each group, demographic data (sex and mean age) and mean scores in intelligence and reading performance tests (percentiles). Values enclosed in parentheses represent standard deviation

Word reading test The objective of this test is to assess lexical processes involved in reading, that is, whether the child is able to carry out a global and immediate recognition of words. It implies reading aloud a list of 42 medium-frequency words in Spanish with different lengths and various degrees of orthographic complexity. Regarding to accuracy, the maximum score for each word (2 points) is obtained if reading is accurate and fast, that is, not hesitant. If reading is accurate (use grapheme-to-phoneme rules well) but not fast (syllable by syllable reading or hesitant), the score is 1 point. The measure of reading speed is based on the time needed to read the 42 words. Cronbach's alpha reliability coefficient is 0.71 and criterion-related validity is 0.51.

Pseudoword reading test The objective of this test is to assess sublexical processes (phonological route), that is, whether the child uses grapheme-to-phoneme conversion rules easily without the possible support of lexical knowledge. It implies reading aloud 42 pseudowords constructed by combining the syllables of the words of the word reading test so that each new pseudoword is equivalent in syllable length and orthographic complexity to one of the words. As in the word reading test, maximum score (2 points) in each item can be obtained if reading is accurate and fast. In case of reading is accurate but hesitant, the score is 1 point. Time is also registered to assess reading speed. Cronbach's alpha reliability coefficient is 0.76 and criterion-related validity is 0.51.

Experiment 2a: implicit sequence learning

The same task as in experiment 1 was used with the following changes: the stimulus used to mark each location was an asterisk instead of the letter X used in the previous experiment (see Fig. 1). This change was made to avoid any possible influence of linguistic material (the letter X) in dyslexic children. Moreover, the number of training blocks was increased from four to seven, so that the task consisted of 11 blocks of trials (see Table 3). The first block was composed of 48 practice trials in which the locations of the asterisk were randomly determined, with the only constraint that repetitions were not allowed in two consecutive trials. The second block was a control block in which four repetitions of the training sequence and four repetitions of the control sequence were presented to assess

Table 3 Experimental design of experiment 2a

Block	Trials	Order
1	48	Random without repetitions
2	48	Presentation of training and control sequences
3	60	Training sequence
4	60	Training sequence
5	60	Training sequence
6	60	Training sequence
7	60	Training sequence
8	60	Training sequence
9	60	Training sequence
10	60	Control sequence
11	60	Training sequence
Generation task	9	

whether both sequences were answered with similar RTs. As in the previous experiment, the training sequence was 3-1-2-1-3-2 and the control sequence was 3-2-1-2-3-1. Training began in the third block. Blocks 3 to 9 and block 11 all presented ten repetitions of the training sequence for a total of 60 trials. Block 10, in contrast, presented the same number of repetitions of the control sequence. As in the first experiment, participants were instructed to respond fast and accurately and were not informed about the presence of any sequence, so that learning could be taken as implicit.

As in the previous experiment, the training and control sequences were not counterbalanced between subjects. Apart from the above-mentioned difference in salience in favor of the control sequence, there was another reason to avoid using this technique: As there were only three second-order sequences formed out of three possible locations that would be statistically analogous and we wanted to conduct two consecutive experiments of sequence learning using the same participants, we considered it safer to use the sequence containing the most salient pattern as the control sequence for both experiments and to assign one of the two remaining sequences as the training sequence respectively for the incidental learning task (experiment 2a) and for the intentional learning task (experiment 2b).

Generation task At the end of the serial RT task, the participants were informed about the presence of a sequence, and they were asked to carry out a generation task devised to assess explicit knowledge of the sequence. The three pairs of brackets were shown empty, and participants were asked to press the response keys on nine successive trials according to the order in which they believed that the asterisks were more often presented over training. No feedback was provided during this task, but children were instructed to try to respond as accurately as possible. This task was scored by counting the number of correct fragments of three locations generated over the nine keypresses.

Results and discussion

In the RT analyses, the first two trials from each block, as well as error responses and outliers (1.8%), were eliminated from the analyses. Accuracy mean was 94.2% and throughout all the analyses there was no indication of a trade-off effect between speed and accuracy. Therefore, we focused only on the description of the RT results.

Table 3 shows the demographic data and the results of the intelligence and reading performance tests carried out by both groups (dyslexic group and control group). As can be seen, the groups were balanced in sex and age and showed no differences in the measure of intelligence. As expected according to the selection made, both groups showed considerable differences in the four measures of reading performance (all p's<0.0001).

Figure 3 shows mean RTs obtained over the entire experiment, plotted separately for the dyslexic and control groups. In the control group, overall RTs decreased across blocks but they suddenly increased over control block 10, when the training sequence was replaced by the control sequence. The dyslexic group did also show a progressive improvement in RT over the training blocks, thus indicating that maybe they were able to learn about the unspecific components of the task. However, they show no significant indication of an increase in RTs over the control block 10, when the sequence was replaced, thus suggesting that the learning acquired by this group was not related to the task following a sequence but rather with other unspecific components which remain invariable over the control block.

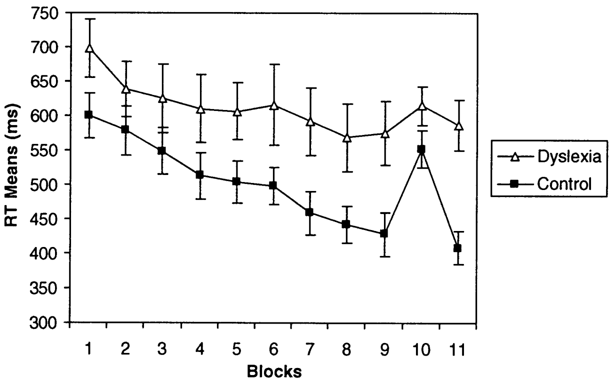


Fig. 3 Mean RT for dyslexic and control groups in experiment 2a across blocks of training. *Error bars* represent standard errors of the mean

A single-factor ANOVA with the Group variable focused on the random block 1 did not show a significant difference between groups, although there was a tendency for the control group to respond slightly faster than the dyslexia group ($F(1, 26)=3.35$; $p=0.08$). In the analysis of the second block, where the training and control sequences were equally likely, the first cycle was again eliminated to control for the effect of the slower first responses. An ANOVA with Group (control vs dyslexic) as between-participants variable and Sequence (training vs control) as within-participants variable failed to reach significance, thus showing that, prior to training, responding to both sequences were roughly equivalent for both groups.

The following analyses focused on the training and control blocks (blocks 3 to 11). An ANOVA with Group (control vs dyslexic) as between-participants variable and block (9 levels) as within-participants variable showed main effects of Group ($F(1, 26)=5.06$, $p=0.03$) and Block ($F(8, 208)=11.84$, $p<0.0001$), as well as a significant Group×Block interaction ($F(8, 208)=3.04, p=0.003$). This interaction showed that the effect of Block was significant in the control group ($F(8, 104)=18.7$, $p<0.0001$) but not in the group of dyslexic children ($F(8, 104)=1.46$, $p=0.18$). To confirm that the effect of block obtained selectively for the control group reflected sequence learning, we compared RT over the control block 10, with the average RT produced over its neighboring training blocks 9 to 11. An ANOVA with Group (control vs dyslexic) as between-participants variable and Type of block (training vs control) as within-participants variable showed a main effect of Group ($F(1, 26)=7.21$, $p=0.02$) and Type of Block ($F(1, 26)=38.33$, $p<0.0001$). The Group× Type of Block interaction also reached significance ($F(1, 26)=13.49$, $p=0.002$). The specific analysis of this interaction revealed an effect of Type of Block in the control group ($F(1, 13)=83.36, p<0.0001$) but not in the dyslexic group ($F(1, 13)=2.24, p=0.16$). The increase in RT observed over the control block 10 and selectively for the control group did unequivocally point to an effect of sequence learning which arose exclusively in the control group but was not observed in the group of children with dyslexia.

Generation task

The maximum number of three-element fragments generated over the nine successive generation trials was 6. The mean of correct fragments was 3.07 in the control group and 2.71 in the dyslexic group. An ANOVA on these scores with the Group variable showed no evidence of significant differences between groups ($F<1$).

Thus, in short, the results of experiment 2a showed no evidence of sequence learning in the group of children with dyslexia, whereas children in the control group showed clear effects of sequence learning over the indirect measures of RT. That difference in the effect of sequence learning was not as clearly observed through the measure obtained from the direct generation task, thus suggesting that the difference between groups could have to do with a specific deficit in implicit sequence learning observed in the group of dyslexic children. Experiment 2b was directed to assess this conclusion.

Experiment 2b: intentional (explicit) sequence learning

The objective of this experiment was to explore whether the deficit in sequence learning shown by dyslexic children in experiment 2a is specific to implicit acquisition or whether it could be taken as the consequence of a broader deficit that may be expressed even when participants are explicitly instructed to look for and to intentionally learn the sequence. To answer this question, the same children who had participated in experiment 2a were recruited to take part in another experiment. Before the experiment began, they were informed about the presence of a sequence and were instructed to try to learn it and to exploit it as a way to improve their performance. To minimize the influence of the previous experience on the following task, several changes were made in the training sequence, in the spatial arrangement of the locations, and in the required response.

Method

Participants

Participants of the dyslexic and control groups were the same as in experiment 2a.

Procedure

About a week after performing the implicit task, participants were instructed to try to learn about a new training sequence. To facilitate the search for a sequential pattern, the three locations were now arranged to occupy the vertices of an invisible triangle. The distance between the centers of the brackets was 3.5 cm (see Fig. 4). Thus, the sequential order of the locations could generate a figure. This new arrangement was also aimed at minimizing the influence of the experiment 2a on performance of the new task. To this end too, the training sequence was different from both sequences used in the previous experiment, and all responses were given using only the index finger of the right hand. Response keys were B-H-N, which form a triangle in the Spanish keyboard, and they have a congruent spatial

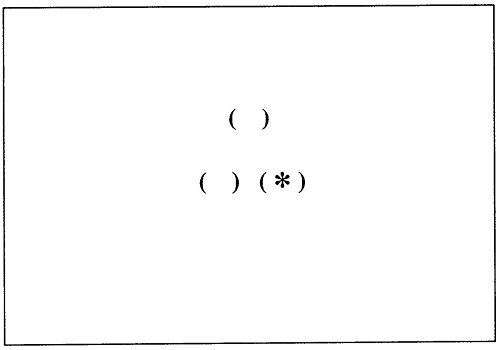


Fig. 4 Example of a trial in the experiment 2b

correspondence with the three possible locations of the stimulus. Participants responded with key B when the asterisk was shown on the left, H when it appeared at the top, and N when it appeared on the right.

The new training sequence was 2-1-3-1-2-3, whereas the control sequence was the same one used as control in experiment 2a (1-2-3-1-3-2). Blocks 1 and 2 had the same structure as described for experiment 2a. After block 2, participants were told about the existence of a sequence and were instructed to learn it as a way to respond faster and more accurately. From block 3 to block 8, participants responded to the training sequence, which was also presented in block 10. In block 9, participants were presented with a control block composed by ten repetitions of the control sequence (see Table 4).

Generation task As in experiment 2a, after the intentional task, participants were required to carry out a generation task. Children were told to press a series of nine keys according to the order they believed that the asterisks have followed most of the time. As the measure of sequence knowledge, we took the number of correct three-element fragments produced over the nine-key series.

Results and discussion

In the RT analyses, the first two trials from each block, as well as error responses and outliers (1.7%), were eliminated from the analyses. Accuracy mean was 94.8% and throughout all the analyses its pattern again mirrored that found for RT measures. Therefore, we focused on the description of the RT results.

The analysis of the first block showed a marginal effect of Group ($F(1, 26)=3.01$, $p=0.09$), reflecting that participants in the dyslexic group tended to respond slower than those in the control group. Regarding the second block, the first cycle of six trials was eliminated to control for the effect of slower initial responses. An ANOVA carried out with Group (control vs dyslexic) and Sequence (training vs control) again showed a marginal effect of Group ($F(1, 26)=3.51$, $p=0.08$), but no effect of Sequence nor interaction between Sequence and Group was (F's<1). These analyses show that, before training, responding to both sequences was equivalent.

Table 4 Experimental design of experiment 2b

Block	Trials	Order
1	48	Random without repetitions
2	48	Presentation of training and control sequences
3	60	Training sequence
4	60	Training sequence
5	60	Training sequence
6	60	Training sequence
7	60	Training sequence
8	60	Training sequence
9	60	Control sequence
10	60	Training sequence
Generation task	9	

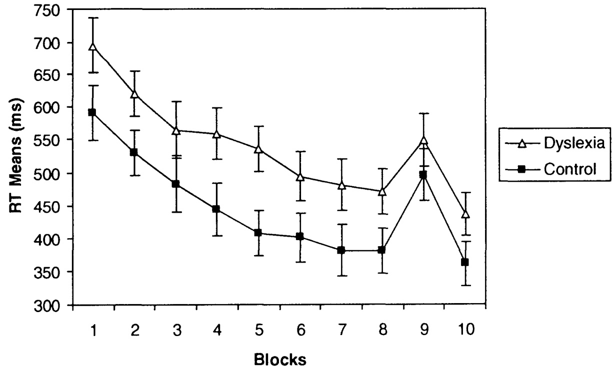
Focusing on the training blocks and the assessment of learning, Fig. 5 shows that both groups differ in the overall RT but that the performance pattern was similar in both groups. A gradual decrease in RTs was observed over training, followed by a sudden increase in RTs over the control block (block 9) and a final decrease over the last training block. Therefore, it appears that both groups had been able to learn the sequence when they were explicitly instructed to do so.

These observations were confirmed, first, through an ANOVA with Group (control vs dyslexic) as between-participants variable and training Block (eight levels) as within-participants variable. This analysis showed a marginally significant effect of Group ($F(1, 26)=4.22$, $p=0.0502$) and a main effect of training Block ($F(7, 182)=9.37$, $p<0.0001$). However, the Group × training Block interaction was not significant ($F<1$), thus showing that the improvement over training was similar in both groups. More relevant to the assessment of sequence learning, the comparison of performance over the control block 9 and the average performance produced over the neighboring training blocks (8 and 10) showed a main effect of type of block (training vs control; $F(1, 26)=23.48$, $p<0.0001$). No significant effect of Group ($F<1$) and no significant interaction Group × Type of Block ($F<1$) were found in this analysis. Moreover, separate analyses of the effect of type of block carried out for each group showed an effect of type of block both in the control group ($F(1, 13)=14.43$, $p=0.002$) and in the dyslexic group ($F(1, 13)=10.6$, $p=0.006$). Therefore, these results confirm that both groups learned the sequence and that the degree of learning was not different between them.

In sum, the results from experiment 2b indicate that children with dyslexia are able to learn a sequence of locations to the same extent than a comparable control group when they are explicitly informed about the existence of a sequence and are encouraged to exploit it. Thus, the deficit obtained in experiment 2a does not seem to obey to a general deficit in sequence learning but rather to a specific impairment with implicit acquisition.

Generation task As in experiment 2a, the generation task was analyzed by scoring each group of three correct fragments with one point. Mean performance was 4.43 correct fragments in the control group and 4.07 in the dyslexic group. The comparison of these means did not show significant differences ($F<1$). Again, this suggests that the amount of explicit knowledge was similar between groups. As expected, a comparison of the performance of the generation task after the incidental task and the intentional task shows that both groups performed better after this second task and therefore that learning was more explicit in this case.

Fig. 5 Mean RT for dyslexic and control groups in experiment 2b across blocks of training. *Error bars* represent standard errors of the mean



In short, experiments 2a and 2b show a deficit in sequence learning in the dyslexic group, which arises specifically when learning is acquired implicitly but not when learning results from an explicit strategy to look for regularities. In light of these results, it comes naturally to ask whether the observed deficit could be generalized to other implicit learning tasks or whether it could depend on the sequential nature of the material involved in the SRT task. Howard et al. (2006) addressed essentially the same issue in a sample of adult people with dyslexia, by using the contextual cueing paradigm (Chun & Jiang, 1998). They found that the dyslexic group showed a specific impairment in the sequence learning task but not in the contextual cueing task. In the following experiment, we aimed to explore the same issue in a sample of children with dyslexia, in order to ascertain whether the results obtained by Howard et al. could indicate that these non-sequential forms of implicit learning are generally preserved in dyslexia at any developmental stage or whether the abilities showed in adults with dyslexia could reflect the operation of some kind of compensatory strategies adopted by adults with dyslexia in order to minimize the consequences of a developmental deficit.

Experiment 3: contextual cueing in dyslexic children

Howard et al. (2006) tested the hypothesis about a general implicit learning deficit in dyslexic adults by comparing sequence learning with another non-sequential learning task, as it is the case of the contextual cueing (Chun & Jiang, 1998). In the contextual cueing paradigm, participants are instructed to look for a target embedded among a series of distractors and to respond in terms of the identity of the target. In a half of the trials, the configuration of distractors covariates with a specific location of the target, so that participants can learn to use these configurations of distractors to improve the search for the target. Differential improvement of RT for trials with repeated and variable contexts show that people are learning to exploit the regularities found in the repeated context to produce a more efficient search for the target.

In the study carried out by Howard et al. (2006), the group of dyslexic adults did not show any deficit in this contextual cueing task, whereas they showed a significant deficit in sequence learning. This pattern was considered as consistent with the fact that cerebellar and striatal deficits, but not temporal deficits, have been observed in dyslexic population. The aim of experiment 3 was to explore whether this dissociation could also be observed in dyslexic children or whether, on the contrary, a more general deficit in implicit learning could be obtained in early developmental stages, before people have the opportunity to develop compensatory strategies to deal with their impairments.

Method

Participants

The sample was composed of 50 children with ages between 8.5 and 9.5 years (mean 9 years). Out of this group, 24 children were included in the dyslexic group (14 boys and ten girls) and 26 formed the control group (16 boys and ten girls) following the same criteria used in experiment 2 (see intelligence and reading performance scores in Table 5). All participants were in the school year that corresponded to their chronological age. None of them had ever been diagnosed with dyslexia or any other disorder, and they all participated for the first time in this type of study.

Table 5 Participants experiment 3

	Male/ female	Age (months)	IQ (RAVEN)	Word reading accuracy (percentile)	Word reading fluency (percentile)	Pseudoword reading accuracy (percentile)	Pseudoword reading fluency (percentile)
Dyslexic Group (n=24)	14/10	107.75 (4.28)	98.75 (7.97)	8.75 (5.16)	10.42 (7.21)	9.17 (6.37)	15.83 (7.21)
Control Group (n=26)	16/10	108.88 (3.59) n.s.	102 (7.65) n.s.	77.3 (12.1) $p<0.0001$	83.84 (11.16) $p<0.0001$	74.04 (9.77) $p<0.0001$	83.84 (9.93) $p<0.0001$

For each group, demographic data (sex and mean age) and mean scores in intelligence and reading performance tests (percentiles). Values enclosed in parentheses represent standard deviation

Apparatus and materials

Intelligence and reading performance were assessed using the same materials as in experiment 2.

Contextual cueing task In this experiment, we adapted to children a contextual cueing task developed by Jiménez & Vázquez (2008, 2010) to use with adults population. The main changes were related to the identity of the target stimulus and the length of the task (details are provided below). This adaptation was tested through a successful pilot study in a sample of children with ages and IQ comparable to those of the target sample and with average reading performance.

The experimental task was designed using INQUISIT 1.31 and Turbo Basic and was administered in a Pentium IV computer. The stimuli were a series of colored digits (yellow, blue, red, or green) shown in Garamond font in a size of 1.3 and 0.8 cm (height × width) on a gray background. Target stimuli were numbers 1 to 4; distractor stimuli were numbers 5, 6, 8, or 9.

To perform the task, children sat in front of the computer at an approximate distance of 40 cm. Each trial presented eight numbers, pseudo-randomly distributed in eight of the 16 possible locations defined by an invisible 4×4 matrix of a size of 11.1×11.1 cm (height × width). The matrix was divided into four quadrants by two black vertical and horizontal lines. Adjacent locations were separated by a horizontal and vertical dis2tance of 2 and 1.5 cm, respectively (see Fig. 6).

Before the start of the session, the software generated a series of trials with the following restrictions: In each trial, a target stimulus and seven distractors were presented. Within a single

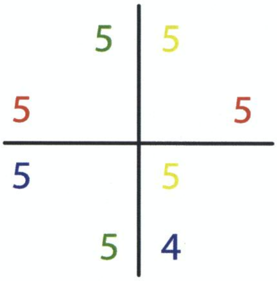


Fig. 6 (Color figure online) Example of a trial in the experiment 3

trial, distractors had all the same identity but could have different colors. In each trial, the eight stimuli were evenly distributed, so that they occupied two of the four possible locations within each of the four quadrants, and two items were drawn in each possible color (yellow, red, green, and blue). The identity of the target and therefore the response required in that trial were generated randomly, with the restrictions that each of the four target identities was presented with the same frequency and two consecutive trials must not present the same target. Regarding target locations, two locations of each quadrant were selected as associated to fixed contexts, whereas the remaining two locations from each quadrant were assigned to variable contexts. In fixed context trials, the appearance of the target in a given location was associated with the global configuration of the distractors (i.e., their identity, locations, and colors), as well as with the color (but not the identity) of the target. In variable context trials, in contrast, all these values could change from trial to trial. Trials presenting the target at each one of the 16 possible locations were presented before the target could reappear at any one of the previously presented locations. Thus, each fraction of 16 trials presented exactly eight trials with a fixed context and eight trials with variable contexts.

Procedure

The training was composed of ten blocks; each of them included six series of 16 trials, which amounted to a total of 960 trials. On each trial, participants had to look for the numbers 1, 2, 3, or 4 among a group of numbers 5, 6, 8, or 9 and to indicate their identity by pressing keys V, B, N, or M with the index and middle finger of each hand, depending on whether the identity of the target was 1, 2, 3, or 4, respectively. Any valid response was followed by the next trial. Participants were instructed to respond as fast and accurately as possible. The session began with a practice block composed of eight random trials. Each block was followed by a break.

Before starting the task, the software selected and assigned two locations of each quadrant as target locations associated to fixed contexts, and the other two as target locations associated to variable contexts. For each of the eight fixed trials, an invariable context was programmed. Importantly, the identity of the target was random in all trials, and therefore, responses were not predictable. Fixed and variable trials were randomly presented in the experiment, in a different order for each participant.

The measure of learning was inferred by comparing performance in fixed and variable trials over practice. If participants learn to use the fixed context as a cue to improve the search for the target number, one could expect a differential effect of training on both types of trials, leading to shorter RTs in response to fixed trials.

Direct measure of contextual cueing At the end of training, a block of 32 trials was included, composed of two repetitions of the eight fixed trials, and of eight variable trials selected from those appeared during the contextual cueing task. In each trial, the identity of the target was replaced by another distractor. The task of participants was to say which quadrant they believed the target would have appeared in that trial according to the current context. Participants responded by pressing the keys of letters T, Y, G, or H depending on whether they thought the target would have appeared in the upper left, upper right, lower left, or lower right quadrant, respectively. To assess to what extent knowledge was more or less conscious, the proportion of trials in which the location (quadrant) of the target was correctly generated was compared between fixed and variable trials. In the training phase, the target was presented in each location with equal frequency; therefore, the proportion expected by chance was 0.25. If knowledge is more explicit, the percentage of correctly generated fixed trials should be greater than that expected by chance. However, if knowledge is implicit, the percentage of correctly generated trials should not be greater than that expected by chance; in any case, it should not be greater in fixed trials than in variable ones. No feedback was provided in this task, and participants were instructed to respond as accurately as possible.

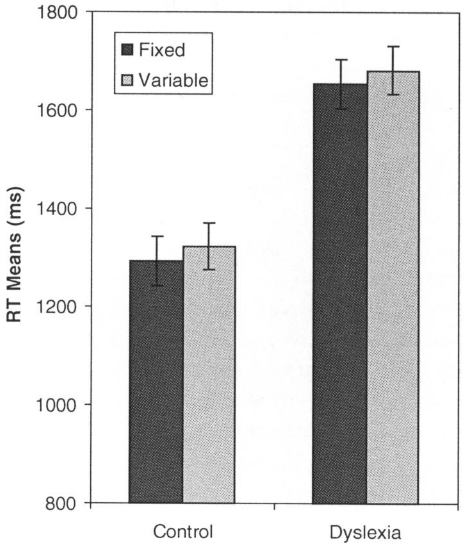
Results and discussion

In the RT analyses, errors were excluded, as well as RTs that differed in more than 3 standard deviations for each participant and block (1.6%). There was no indication of a trade-off effect between speed and accuracy. Therefore, we focused on the RT analyses.

Figure 7 shows RTs of the dyslexia and control groups in each of the contexts. RTs were analyzed with a repeated measures ANOVA considering Group (dyslexic vs control) as between-groups factor and Practice (blocks 1–10) and Context (fixed vs variable) as within-subject variables. The analysis showed that responses were significantly faster for control than for dyslexic groups ($F(1, 48)=26.79$, $p<0.0001$ (1,308 vs 1,667 ms)) and that RT improved with Practice ($F(9, 432)=87.28$, $p<0.0001$). More importantly, spatial context learning was revealed by faster responses to fixed than to variable trials ($F(1, 48)=12.12$, $p=0.002$ (1,473 vs 1,502 ms)). This context learning effect was not different between groups, as the only significant interaction involving groups was the two-way Group × Practice interaction ($F(9, 432)=2.17$; $p=0.02$), showing that participants in the control group improved more with training for both fixed and variable trials. No interaction involving Group and Context approached significance (rest of F's<1). A separate analysis carried out for each group confirmed that the effect of Context was significant in each group separately, both for the control ($F(1, 25)=7.15$; $p=0.02$ (1,293 vs 1,323 ms)) and for the dyslexic group ($F(1, 23)=5.12$; $p=0.03$ (1,653 vs 1,681 ms)).

Direct measure of contextual cueing The percentages of correct responses in fixed and variable trials for each group were not different from those expected by chance (25%), and they did not

Fig. 7 Mean RT for dyslexic and control groups as a function of the type of context in experiment 3. *Error bars* represent standard errors of the mean



differ between fixed and variable trials (28.6 vs 24.7 in the dyslexic group and 25.6 vs 23.3 in the control group). An ANOVA performed on those percentages considering Group (dyslexic vs control) as between-groups factor and Context (fixed vs variable) as within-subject variable showed no significant main effects (Group, $F(1, 48)=1.47, p=0.23$; Context, $F(1, 48)=1.74, p=0.19$) or interaction ($F<1$), thus suggesting that knowledge was implicit in both groups.

In short, results of experiment 3 showed that participants in the dyslexic group responded slower than those in the control group but that the effect of context learning was similarly obtained in both groups. Besides, the direct measure of contextual cueing suggests that learning was implicit in both groups. These results extend those found by Howard et al. (2006; see also Bennett, Romano, Howard, & Howard, 2008) in adults to the population of dyslexic children, thus confirming that the deficit in implicit learning observed in the dyslexic population appears to be restricted to those learning effects involving the acquisition of sequence information.

General discussion

This study provides new evidence on the existence of a deficit in implicit sequence learning in dyslexic children. Moreover, it also shows that this deficit is specific to implicit sequence acquisition, since it is not observed when learning is intentional or when implicit learning does not involve sequential information.

Previous studies exploring the hypothesis of a deficit in implicit sequence learning in dyslexic children have not obtained conclusive results, presumably because of the diversity of methods employed by each study. Although most of these studies have used variants of the serial reaction time (SRT) task, differences concerning the complexity of the training sequences, the type of control trials against which the acquired knowledge is assessed, and the demographic features of the selected sample have all led to inconsistent conclusions. For instance, Waber et al. (2003) found no difference between their two groups in sequence learning performance, testing children with good or poor reading abilities, and providing only four blocks of training with a second-order sequence before testing participants over a random block. A similar null result was also reported by Rüsseler et al. (2006) using a sample of adults and providing a much longer training period before introducing a random control block. In contrast, Vicari et al. (2003, 2005) observed an implicit learning deficit in dyslexic children comparing training over either first-order or second-order sequence with a random control block, and Howard et al. (2006) reported a significant deficit on a similar sample of young adults using a complex alternating structure, in which sequentially predictable trials were continuously interspersed with random trials.

We have identified a number of methodological issues that could potentially account for these apparently contradictory results. First, there is a wide diversity in the criteria used to classify participants into dyslexic or normal readers. In some previous studies, the tests used to diagnose dyslexia provide only a partial assessment of reading processes. Indeed, in most cases, they rely exclusively on the lexical processes, and when they also assess sublexical (phonological) processes, they do not provide measures of reading speed. In this sense, several authors have suggested that, to assess reading difficulties, it is essential to measure the functioning of both reading routes (Castles & Colheart, 1993; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; Sprenger-Charolles & Serniclaes, 2003) as well as accuracy and speed in each of them (Serrano & Defior, 2008; Jiménez-González & Hernández-Valle, 2000; Sprenger-Charolles, Colé, Lacert & Serniclaes, 2000; Wolf & Bowers, 1999). The present study used a reading test that assessed both lexical and sublexical processes and also measured reading accuracy and speed. Thus, it provided four measures of reading performance that led to a more thorough assessment of the processes involved in word recognition and therefore to a more reliable classification of dyslexia (in this case, scores below the 25th percentile in all four measures of reading). Moreover, it is worth emphasizing that participants selected for the present study had no previous diagnosis of dyslexia and therefore had not been submitted to any specific intervention that might have promoted the development of compensatory strategies that might have masked any underlying deficit.

Second, compensatory strategies may also be a factor that helps to understand the differences obtained between studies using samples of adults or children. Since adults with dyslexia may have developed a number of explicit strategies aimed at compensating any possible deficit involving their implicit learning processes, we highlight the convenience of focusing the analysis of possible impairments of implicit sequence learning on the comparison of samples of average readers and non-diagnosed children with dyslexia.

Third, the specific nature of the training sequences and of the control blocks to assess learning may also be important in accounting for the inconsistent pattern of results. On the one hand, using a sequence with an unbalanced number of items of each class will preclude any valid interpretation of the results in terms of sequence learning, since learning about the relative frequency of each item can account for the pattern of results, even in the absence of any sequence learning effect (Reed & Johnson, 1994). Unfortunately, this basic methodological issue still arises frequently in the area (e.g., Stoodley et al., 2006; Stoodley, Ray, Jack & Stein, 2008; Vicari et al., 2003; 2005), and it makes it hard to draw clear conclusions from these studies. Moreover, even in cases in which the training sequences are balanced, as is the case of the studies by Waber et al. (2003) or Rüsseler et al. (2006), we have identified the use of random stimuli over the control blocks as a potential problem, since the increase in reversals which are typically included over those random blocks may result in slower performance, which could be inadvertently attributed to sequence learning (Vaquero et al., 2006).

The present series of experiments were set up to explore these issues in an integrated way. Experiment 1 tested a group of children with a second-order sequence (3-2-1-2-3-1) similar to that used in Waber et al. (2003). However, we assessed sequence learning over a control block in which, instead of resorting to a random block, we introduced a new sequence which differed from the training sequence in most of their transitions, but which crucially had the same number of reversals and was generated simply by exchanging two items from the original sequence. Participants' performance before training confirmed that responses to reversals were about 80 ms slower than responding to any other trial. When the effect of reversals was controlled by arranging a proper control block, we did not find any reliable evidence of sequence learning in typically developing children after an amount of training comparable to that administered by Waber et al. (2003).

In experiment 2a, the number of training blocks was increased to ensure that participants would have time to develop an effect of sequence learning. The performance of a group of dyslexic children was compared to that of a group of good readers. On this occasion, results showed a clear learning deficit in dyslexic children. To rule out the attribution of these differences to an augmented effect of explicit learning produced selectively in the control group, as argued by Rüsseler et al. (2006), we included a generation task in which participants were directly instructed to generate a set of trials resembling the sequence they were trained with. However, no difference between groups was obtained in this task.

In sharp contrast with the argument that "learning deficits found in these studies might be related to explicit, but not implicit learning" (Rüsseler et al., 2006, p. 821), in experiment 2b, participants were presented with a new sequence learning task, but they were told about the presence of a regular sequence and were encouraged to attempt to discover the sequence in order to improve their performance. With these intentional instructions, both dyslexic and control groups showed comparable effects of sequence learning as judged by the increase in RTs produced by the introduction of an untrained sequence over a control block. Therefore, the combined results of experiments 2a and 2b do strongly indicate that dyslexic children show a deficit specific to implicit sequence learning rather than a general impairment in the acquisition of sequence knowledge. In other words, the deficit appears to be related more to the non-intentional processes that continuously allow our cognitive systems to fine-tune their responses to sequential regularities rather than with the efficiency of their explicit attempts to capture and exploit such regularities. These results are in line with previous studies such as those of Vicari et al. (2003), in which a sequence learning deficit was observed in poor readers when participants carried out the task conventionally but not when they were instructed to memorize the sequence beforehand (also see similar data with categorical learning in Sperling et al., 2004).

In experiment 3, the contextual cueing task was used to explore whether an implicit learning deficit could also arise in non-sequential forms of implicit acquisition. In this case, dyslexic children showed a level of learning comparable to that obtained by the control group. Therefore and in line with the results obtained by Howard et al. (2006) and Bennett et al. (2008) with dyslexic adults, our results suggest that the deficit is also specific to sequential information in dyslexic children.

The deficit pattern obtained in this study is consistent with other dissociations observed in both children and adults with dyslexia in stimulus identification tasks. In these cases, deficits were observed when stimuli were presented sequentially but not when they were presented simultaneously/spatially (Ben-Yehudah, Sackett, Malchi-Ginzberg & Ahissar, 2001; Conlon, Sanders & Zapart, 2004; Eden, Stein, Wood & Wood, 1995; Ram-Tsur, Faust & Zivotofsky, 2006).[1] In the study by Eden et al. (1995), children's reading performance correlated with performance of a dot counting task when the dots appeared in succession at any point on the screen (0.40) but not when all the dots appeared simultaneously in an analogous spatial task. Along the same lines, Conlon et al. (2004) reported that adults' performance in the sequential version of the counting-dots task predicted 19% of the variance in a word reading test after variables such as intelligence, verbal memory, and processing speed had been controlled for. In the present study, correlations were calculated between measures of learning and reading performance. In line with the mentioned studies, the measure of implicit sequence learning obtained in experiment 2a correlated significantly with children's reading performance ($r=0.58$, $p=0.005$). In contrast, neither the intentional task (experiment 2b) nor the measure of learning in the contextual cueing task (experiment 3) showed significant correlations with reading performance ($r=0.18$ and $r=-0.05$ respectively). Therefore, this evidence suggests the existence of a relationship between reading skills and other basic skills involving the processing of sequence information.

What does the observed deficit in implicit sequence learning tell us regarding problems concerning the acquisition of written language? In other words, which could be the nature of the link between dyslexia and such a deficit in implicit sequence learning? Previous studies that found a similar deficit in dyslexia suggested that this deficit could prevent the

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[1] Some authors argue that the tendency observed in people with dyslexia to process information holistically may be due to this difficulty in processing sequential stimuli (Facoetti & Molteni, 2001; Hari & Renvall, 2001; Pothos & Kirk, 2004).

automatization of skills, including reading (Howard et al., 2006; Vicari et al., 2005). Indeed, several studies have shown that people with dyslexia have difficulties automatizing skills. For example, it has been observed that dyslexics do not improve with practice in non-linguistic procedural tasks (e.g., the peg moving task, Stoodley & Stein, 2006; or the mirror drawing task in Vicari et al., 2005) or that they do not show optimal automatization in motor coordination (Wolf, Michel, Ovrut & Drake, 1990) or motor balance (Nicolson & Fawcett, 1990, 1994). Based on these findings, Nicolson, & Fawcett (1990) proposed that problems in reading acquisition are a specific manifestation of a general deficit in skill automatization. Nevertheless, these authors also noted that the automatization deficit can sometimes be masked by the use of conscious compensatory strategies that are preserved in dyslexic people. Therefore, automatization problems are only evident in complex tasks, double-task conditions, or when fast processing of stimuli is required. Various neuro-imaging studies have revealed a lower cerebellar activity in dyslexic people, and it has been suggested that this lower activation may explain the automatization problems detected (Fawcett & Nicolson, 1999; Menghini et al., 2006; Nicolson, Fawcett & Dean, 2001; Nicolson & Fawcett, 2007).

Automatization is the mark of good reading skill, and it is manifested when the readers apply grapheme-to-phoneme conversions very fluently and when they have developed orthographic representations that facilitate word recognition (Van der Leij & Van Daal, 1999). Although grapheme-to-phoneme correspondence rules (GPCR) are explicitly taught at school, they only become automatized after extensive practice. Such stages may involve implicit learning processes and particularly sequence learning processes. Specifically, the existence of a deficit in implicit sequence learning could make it difficult for a dyslexic individual to learn regularities in transitions between letters and thus to automatize sequences of GPCR for these regularities. Finally, some authors have suggested that this lack of automatization (fluency) can make it difficult to establish solid representations of words, on both phonological and orthographic levels (Hari & Renvall, 2001; Howard et al., 2006; Sperling et al., 2004).

Regarding the assessment of and the intervention in dyslexia, the existence of a deficit in implicit sequence learning underlines the importance of assessing these processes and intervening with the help of explicit strategies. As pointed out by Vicari et al. (2003), an early assessment of implicit sequence learning may indicate future difficulties in learning to read, which would make it possible to take preventive measures and to carry out early intervention. As for the scope of intervention techniques, our results point out to the usefulness of explicitly teaching some of the regularities of the alphabetic code that are not usually taught this way. One of these regularities would be the frequency in which certain graphemes (and phonemes) appear consecutively, since one of the problems underlying dyslexia may be the difficulty to learn these regularities implicitly. Moreover, although our results have confirmed the existence of a deficit in implicit sequence learning, it does not mean that learning cannot occur implicitly with greater practice. Future research is needed to explore whether these problems in the implicit acquisition of sequences can be understood as a question of degree.

In summary, this study provides strong evidence for the existence of a deficit in implicit sequence learning in dyslexic children and points to a number of key elements which are useful to understand why previous studies have reached inconsistent results. It also shows that the deficit in sequence learning is specific to implicit processes, as it is not observed when participants are explicitly instructed to learn an analogous sequence. Moreover, the deficit in implicit learning is not generalized to any form of implicit learning, but it appears to be specific of sequential regularities. Even though grapheme-to-phoneme correspondences are mainly taught explicitly in the process of learning to read, it has been proposed that implicit learning mechanisms may play a prominent role not only in the automatization of these mappings and in their fluent sequentiation but also in the acquisition and fluent reading of many regularities that are not explicitly taught (Howard et al., 2006; Vicari et al., 2005). Future studies could be targeted to assessing this possibility and therefore to study whether a deficit in implicit sequence learning can be a causal factor of problems in achieving fluent reading.

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