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Article *in* Annals of Dyslexia · October 2015

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Ann. of Dyslexia
DOI 10.1007/s11881-015-0116-9

Implicit learning of non-linguistic and linguistic regularities in children with dyslexia

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Received: 21 January 2015 / Accepted: 27 August 2015
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Abstract One of the hallmarks of dyslexia is the failure to automatise written patterns despite repeated exposure to print. Although many explanations have been proposed to explain this problem, researchers have recently begun to explore the possibility that an underlying implicit learning deficit may play a role in dyslexia. This hypothesis has been investigated through non-linguistic tasks exploring implicit learning in a general domain. In this study, we examined the abilities of children with dyslexia to implicitly acquire positional regularities embedded in both non-linguistic and linguistic stimuli. In experiment 1, 42 children (21 with dyslexia and 21 typically developing) were exposed to rule-governed shape sequences; whereas in experiment 2, a new group of 42 children were exposed to rule-governed letter strings. Implicit learning was assessed in both experiments via a forced-choice task. Experiments 1 and 2 showed a similar pattern of results. ANOVA analyses revealed no significant differences between the dyslexic and the typically developing group, indicating that children with dyslexia are not impaired in the acquisition of simple positional regularities, regardless of the nature of the stimuli. However, within group *t*-tests suggested that children from the dyslexic group could not transfer the underlying positional rules to novel instances as efficiently as typically developing children.

Keywords Developmental dyslexia · Implicit learning · Positional regularities

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Published online: 22 October 2015

Although a phonological deficit is currently the most widely accepted explanation of developmental dyslexia (DD) (Snowling & Stackhouse, 2006), a recent line of research suggests the possible existence of an underlying implicit learning deficit (Folia et al., 2008). Such a deficit could partially explain why individuals with DD persistently struggle to automatise orthographic regularities despite appropriate instruction and repeated exposure to print.

Implicit learning is conceptualised as the acquisition of knowledge, which is representative of the structure of a certain environment, in the absence of conscious effort to learn and which can be used to solve problems and make decisions about novel circumstances (Reber, 1967, 1993). Studies carried out with typical populations suggest that implicit learning indeed plays an important role in literacy acquisition as it enables subjects to acquire orthographic regularities which are not explicitly taught through formal education (Pacton, Fayol, & Perruchet, 2005; Pacton, Perruchet, Fayol, & Cleeremans, 2001). Moreover, it has been shown that the ability to implicitly learn regularities is related to both childrens' and adults' reading skills in such a way that subjects who achieve higher scores in an implicit learning task also perform better on standardised reading tests (Arciuli & Simpson, 2012; Sperling, Lu, & Manis, 2004).

Considering the importance of implicit mechanisms in reading and spelling acquisition, authors such as Gombert (2003) have highlighted the relevance of studying implicit learning processes in individuals with dyslexia. Within this research field, the sequence learning task and the artificial grammar learning task (AGL) have been the most utilised paradigms.

Sequence learning task

The typical sequence learning task consists of a serial reaction time task (SRTT; Nissen & Bullemer, 1987), where participants view a continuous sequence of stimuli and are required to indicate as fast as possible the position of certain targets. Unknown to participants, the positions follow a specific sequence that is repeated throughout the task. As participants view more blocks of stimuli and perform the task, they become progressively sensitive to this sequence. This is evidenced by the fact that reaction times (RTs) tend to decrease with successive blocks, but they increase significantly when a randomly ordered block is introduced. Through this paradigm, some authors have found that children with DD were impaired in learning sequences as their RTs did not significantly increase with the introduction of random sequences (Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011; Stoodley, Ray, Jack, & Stein, 2008; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). Similar results have been reported for dyslexic adults (Du & Kelly, 2013; Howard, Howard, Japikse, & Eden, 2006; Stoodley, Harrison, & Stein, 2006) supporting the hypothesis of an implicit learning deficit as a persistent feature of dyslexia. These results, however, are contentious as other studies have found evidence of preserved implicit learning in both children and adults with dyslexia (Kelly, Griffiths, & Frith, 2002; Menghini et al., 2010; Roodenrys & Dunn, 2008; Rüsseler, Gerth, & Münte, 2006). Such inconsistent results may be explained by differences in the methodological approaches, as suggested by Lum, Ullman, and Conti-Ramsden (2013). These authors conducted a meta-analysis of 14 SRTT studies and found a large degree of variability related to the age of participants, the tasks used and the relative difficulty of each task. Another relevant issue is the inclusion criteria established for participants, which vary among studies in terms of assessment measures and reading thresholds to be regarded as having dyslexia.

It is important to note that although sequence learning tasks have been widely used to study implicit learning in poor readers, most studies have not included linguistic stimuli in their tasks. Thus, these studies have avoided the impact of language in the learning of the regularities. If dyslexia is caused by a factor specifically related to the processing of print, studies which use only non-linguistic material are unlikely to find any difference between dyslexic and control participants. We are aware of just one SRTT study carried out with dyslexic adults that included linguistic information (Gabay, Schiff, & Vakil, 2012). The participants heard the name of a letter and were asked to identify its position within a letter string. Results showed that participants with dyslexia were able to learn the sequences embedded in the letter strings similarly to control participants. However, this task not only provided visual linguistic information, as it also activated auditory processes. These auditory processes may have facilitated learning, thus masking a possible deficit in the visual domain.

Another point to note regarding sequence learning tasks is that they generally contain a motor component for the response, which has led some authors to argue that they not only tap the learning of visual sequences but also visual-motor procedural learning (see Goschke, 1998, for a review). Thus, participants who perform poorly on sequence learning tasks might have an impairment in learning the visual-motor response as opposed to a sequence learning deficit.

Artificial grammar learning task

This task (created by Reber, 1967) has no motor component and is thus believed to assess the implicit learning of visual regularities without the additional visual-motor demands. In the AGL paradigm, stimuli are created by using a small artificial grammar that determines which letters can legally succeed others. The task typically consists of an exposure phase where grammatical exemplars are displayed and a later test phase in which the occurrence of implicit learning is assessed. In this latter phase, novel grammatical and ungrammatical stimuli are displayed and participants are requested to indicate the grammaticality of each stimulus. Although there is no clear consensus on what content is actually learned in an AGL task (i.e., exemplars, chunks or rules), some authors suggest that it explores the ability to both abstract complex rules as well as transfer these rules to novel circumstances (see Pothos, 2007 for a review).

Through an AGL task, Pavlidou, Williams, and Kelly (2009) investigated the abilities of children with DD to implicitly learn regularities that were embedded in shape strings. Results showed that control participants were able to acquire the regularities, whereas participants from the DD group exhibited no evidence of learning. This pattern of results was corroborated by follow-up studies (Pavlidou, Kelly, & Williams, 2010; Pavlidou & Williams, 2014), thus supporting the existence of an implicit learning deficit in individuals with DD. However, a contrary finding was reported by Pothos and Kirk (2004). Although these authors used the same AGL task as Pavlidou et al. (2009), they found an unusual pattern: not only could participants with dyslexia learn the regularities of the grammar, but they also outperformed participants from the control group. Such contrasting results between Pothos and Kirk's study and the work of Pavlidou et al. could be explained by key differences between the samples—for example, differences in the age of the participants and the fact that Pothos and Kirk used a far less stringent inclusion criteria for their dyslexic group.

While the previously described studies investigated the implicit learning of non-linguistic patterns, another AGL study explored the acquisition of linguistic regularities in children with poor spelling skills (Ise, Arnoldi, Bartling, & Schulte-Körne, 2012). In this study, letter strings were generated by two artificial grammars: one containing pronounceable strings (CVCVC) and the other containing non-pronounceable strings (CCCCC). Results showed that although poor spellers were above chance at identifying high-frequency patterns in both conditions, they nevertheless performed significantly worse than control participants. In addition, the analysis of training item recognition revealed that good spellers benefited from the linguistic component, whereas poor spellers did not. However, the results of this study cannot be generalised to individuals with DD as children who showed difficulties in sentence reading (a potential indication of DD) were excluded from the study. Nevertheless, the fact that poor spellers were impaired in the acquisition of linguistic regularities suggests that assessing the implicit learning ability of dyslexic individuals using linguistic and non-linguistic material may be revealing.

To summarise, there is much heterogeneity in the results of studies which have explored the possible link between dyslexia and implicit learning. This heterogeneity may suggest that implicit learning mechanisms do not operate in an all-or-none fashion, and instead, may depend upon the features of the sample and the complexity of the learning task. Hence, in order to explore whether an implicit learning deficit is a contributing factor to dyslexia, the focus should be placed on exploring which regularities individuals with dyslexia can and cannot acquire through implicit mechanisms.

One important point to note is that previous research has largely focused on the implicit learning of visual regularities in a general domain. To our knowledge, no study has yet investigated the implicit acquisition of orthographic patterns in children with DD; nor has any study compared this ability to the learning of non-linguistic regularities.

The current study

The current study explored whether children with DD were impaired in the implicit acquisition of positional patterns and whether the introduction of linguistic information affected this acquisition. We selected for possible inclusion in the study children who were in third grade (8 and 9-year-olds) since it is in this grade when difficulties in reading fluency tend to manifest in Spanish. As previously noted, most researchers have explored dyslexics' implicit learning abilities with visual tasks that excluded orthographic cues. Thus, it is not clear whether dyslexics' spelling difficulties are due to difficulties in the acquisition of rules in a visual domain or whether their performance is affected by the introduction of linguistic information. In order to explore this question, we designed two learning tasks where identical positional regularities were embedded within non-linguistic and linguistic strings.

In experiment 1, abstract shapes were introduced in order to produce four-element stimuli ($S_1S_2S_3S_4$), which lacked visual familiarity and possessed no phonological cues, thus preventing verbalization. In experiment 2, we explored children's implicit learning of linguistic regularities embedded in a consonant vowel consonant vowel (CVCV) structure, a very common word structure in Spanish.

The non-linguistic task was tested in a pilot study with 17 typically developing (TD) children aged 8–9 years, with the mean level of correct responses being 59.7 % (SD=16.4, range 43.7–96.9). The linguistic task was tested in a previous study carried out with 26 TD children of the same age (Nigro, Jiménez-Fernández, Simpson, & Defior, 2015), and participants obtained a mean level of correct responses overall of 61.4 % (SD=12.1, range 40.6–84.4). Importantly, there was no significant difference in performance between these two groups (t_{41}=3.86, p=.701), thus suggesting that these tasks elicit a similar level of implicit learning in TD children. Given that the children in the present study are of a similar age, we expected similar amounts of implicit learning to be found in the TD group.

If children with DD have a language specific implicit learning impairment, they would be expected to show lower levels of implicit learning compared to TD participants in experiment 2, but not in experiment 1. In contrast, if children with DD have a general visual implicit learning deficit (not specifically related to the learning of linguistic material), they would be expected to show lower levels of implicit learning than control participants in both experiments. Finally, if children with DD were not impaired in the implicit learning of positional rules, they would be expected to show similar levels of learning as control participants in both experiments.

Experiment 1: implicit learning task without linguistic content

Method

Participants. Seventy third-grade students were selected by their teachers as candidates for the experimental group (DD) as they showed persistent reading difficulties in the absence of behavioural indicators of comorbid disorders (such as attention deficit or language impairment) or major social problems (such as frequent school absences). None of the participants had received any clinical treatment for their reading difficulties. From this candidate group, a final sample of 21 children (16 boys and 5 girls) was selected such that all participants had average to high non-verbal IQ (equal to or above 90 in Raven's test), along with poor reading skills. Poor reading was defined as a score equal to or below the 25th percentile in reading accuracy of words and pseudowords from test LEE (see "Materials and apparatus"). Since Spanish is a transparent orthography, inaccurate reading is a clear indicator of reading problems. Reading speed was also measured and although most of these children were below the 25th percentile on this measure, a small number had a reading speed above this percentile. However, the high error rate for these children, along with information provided by teachers leaves no doubt about the diagnosis of DD.

The 21 participants with DD were matched by age, gender and IQ with 21 control subjects. Controls were selected to have good reading skills, defined as a score equal to or above the 50th percentile in both reading accuracy and reading speed of words and pseudowords (test LEE).

All participants were native Spanish speakers, came from a similar middle-class background, lived in the same district and attended the school grade that corresponded to their chronological age. A summary of the two groups' non-verbal IQ and reading abilities is presented in Table 1.

Materials and apparatus

Word and pseudoword reading Participants' reading skills were measured using the word and pseudoword reading tasks from the standardised test LEE (Defior et al., 2006). The word reading task consists of a list of 42 words of medium frequency which vary in length and

Table 1 Mean scores and (standard deviations) of non-verbal IQ, word reading accuracy and reading speed, and pseudoword reading accuracy and reading speed broken down by group: developmental dyslexia (DD) and typically developing(TD)

Group	Non-verbal IQ	Word reading accuracy	Word reading speed	Pseudoword reading accuracy	Pseudoword reading speed
DD	96.3 (8.7)	12.1 (5.4)	24.8 (19.3)	12.1 (4.3)	36.2 (24.1)
TD	98.1 (10.4)	75.8 (14.9)	83.7 (9.4)	68.9 (12.6)	76.8 (19.4)

orthographic complexity. A maximum of 2 points can be awarded for each item with 1 point awarded for correct decoding and a further point for normal fluency (i.e., absence of repetitions or syllabic reading). Reading speed (i.e., the time spent to read all items) was also assessed.

The pseudoword reading task also includes 42 items, made up by combining syllables extracted from the word reading task. Reading speed was also assessed and scoring criteria was identical to the word reading task.

Intelligence Intellectual capacity was estimated using the Raven's Coloured Progressive Matrices (Raven, Court, & Raven, 1996), which provides a measure of non-verbal IQ.

Implicit learning of non-linguistic regularities Stimuli for the implicit learning task consisted of four-shape strings ($S_1S_2S_3S_4$) formed from a set of 10 abstract shapes based on Fiser and Aslin (2001) (see "Appendix"). Three specific shapes could be embedded in S_1 and three different shapes in S_3. The remaining four shapes could appear in both S_2 and S_4, thus giving a total of 144 possible legal combinations. Thirty-six strings were selected for inclusion in the exposure phase. Eight of these were also selected for inclusion in a later test phase as *legal seen* stimuli (see "Procedure"). Another set of eight legal items, not used in the exposure phase, was selected from the remaining 108 possible legal combinations to be used as *legal unseen* stimuli (i.e., not seen in the exposure phase and therefore, they could not be memorised prior to the test phase). The 16 legal stimuli were used to generate the 16 illegal stimuli introduced in the test phase. This was done by exchanging the position of S_1 and S_3 in each instance (i.e., $S_3S_2S_1S_4$). The legal items were randomly combined with the illegal items to form 16 pairs. In the test phase, each pair was shown twice to give a total of 32 test trials for each subject with the position of the legal items counterbalanced (left vs right).

Explicit learning The possibility that children gained explicit knowledge about the orthographic rules was assessed through a short questionnaire with the following two questions: "If another child came to play this game, what piece of advice would you give her/him in order to solve it?" and "Did you notice anything special about these words?".

Procedure. The test battery was individually administered in two sessions. The non-verbal intelligence test and the reading test were administered in the first session, while the implicit learning task was administered between 2 and 8 weeks later in the second session. This task was presented utilising the E-Prime 2.0 software (Schneider, Eschman, & Zuccolotto, 2002).

In order to create an engaging environment, the experiment was introduced as a game and the evaluator explained that participants who won the game would receive stickers (stickers were given to all participants regardless of their performance).

The experiment was administered in two phases: an *exposure phase*, where legal stimuli were displayed, and a *test phase*, where pairs of stimuli were displayed, one stimulus being legal (previously seen or unseen) and one illegal (and therefore not seen before). Between phases, a distractor task was introduced consisting of six 1-digit additions.

In the exposure phase, participants were told that they would see words from a new language, though nothing was said about the positional constraints. Stimuli were presented in three blocks separated by short breaks. Each block contained the 36 legal items presented in a random order and, thus, at the end of the exposure phase participants had seen 108 items. Each trial started after a blank screen (400 ms) and a fixation point (400 ms), and it consisted of displaying one figure in position 1 and adding subsequent figures in positions 2, 3 and 4 at intervals of 150 ms.[1] Once the whole stimulus was completed (that is, all four components were visible), it remained on screen for a further 150 ms. In order to maintain attention, 12 randomly selected stimuli (3 per block) were displayed in red as opposed to the usual black and participants were asked to push the spacebar as soon as they saw a red “word”.

Immediately after the distractor task, the test phase was introduced and participants were asked to identify words from the new language. There were two blocks of 16 trials, each containing a pair of stimuli (one legal and one illegal) placed one next to the other in the centre of the screen. The administrator explained that only one item in each pair was a word and that participants should decide which one by pressing one of two keys that corresponded to the position of the stimuli on the screen. There was no time limit to respond and no feedback was given. The experiment was administered in one session of approximately 15 min, depending on how quickly each participant responded during the test phase. The questionnaire exploring explicit knowledge was administered immediately after the experiment.

Data analysis

There were two dependent variables in the experiment: percent correct responses for seen and unseen items. The occurrence of implicit learning was assessed using one-sample *t*-tests comparing the performance of each group against chance level (50 %). In order to explore the possibility of an implicit learning deficit within the DD group, a mixed analysis of the variance (ANOVA) was run with one within subject factor corresponding to type of legal stimuli (seen and unseen) and one between subject factor corresponding to group (DD and TD).

Results

All participants were retained for analyses as none showed evidence of explicit knowledge about the positional rules when answering the explicit learning questionnaire. Independent-sample *t*-tests confirmed no differences between the two groups in terms of IQ (t_{40}=.61, p=.544, r=.10) but significant differences in terms of word reading accuracy (t_{40}=37.73, p<.001, r=.99); word reading speed (t_{40}=12.05, p<.001, r=.88); pseudoword reading accuracy (t_{40}=9.45, p<.001, r=.83); and pseudoword reading speed (t_{40}=5.84, p<.001, r=.68).

Figure 1 summarises the average correct response rate in the test phase for all items (32), seen items (16) and unseen items (16) separately for the DD and the TD group. In the DD group, 15 participants (71.4 %) performed above chance level in the overall task, whereas 16 participants (76.1 %) performed above chance in the TD group.

No significant differences were found between the performance of participants across block 1 or 2 (p>.05) for either group; thus, results were collapsed across blocks in all subsequent analyses. Results from one-sample *t*-tests showed that participants from the TD group performed above chance level in all three cases (overall: M=58.78, SD=10.44, t_{20}=3.85, p=.001, r=.65; seen items: M=57.14, SD=14.15, t_{20}=2.31, p=.032, r=.46; unseen items: M=60.42, SD=12.55, t_{20}=3.80; p=.001, r=.65). Of note, overall performance was very

[1] Shapes were sequentially added as a previous pilot study with a sample of TD third graders showed that participants could only learn the visual regularities when each shape was added to the display one-at-a-time (instead of presenting all four shapes at once).

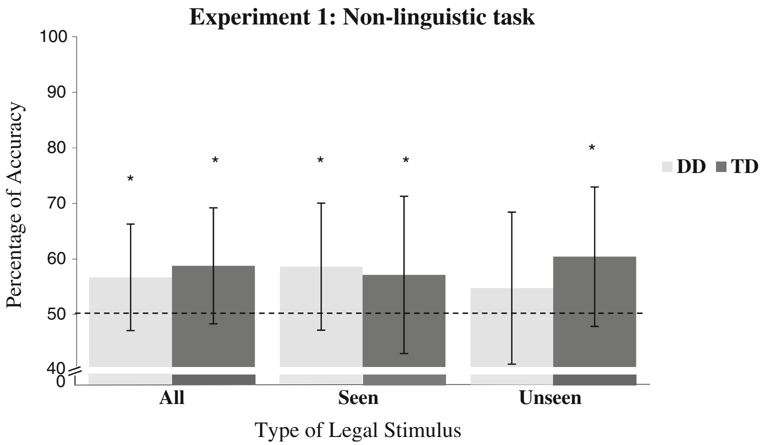

Fig. 1 Participants' mean accuracy for all, seen and unseen items, separately for the developmental dyslexia (DD) and the typically developing (TD) groups. *Error bars* represent ±1 standard deviation from the mean. An *asterisk* indicates performance significantly above chance (*dashed line*)

similar to that found in the pilot study, thus suggesting that the task evokes similar levels of implicit learning with similar samples. Participants with DD also performed above chance level in the overall task (M=56.70, SD=9.59, t_{20}=3.20, p=.005, r=.58). However, when seen and unseen items were analysed separately, performance on seen items was above chance (M= 58.63; SD=11.43, t_{20}=3.46, p=.002, r=.61), whereas performance on unseen items did not reach significance (M=54.76; SD=13.68, t_{20}=1.59; p=.126, r=.33) thus suggesting some difficulty in transferring the underlying rules to novel instances.

The mixed ANOVA revealed no significant main effect of group (F [1, 40]=.45, p=.505, r=.10) or type of legal stimuli (F [1, 40]=.01, p=.908, r=.02). The interaction between group and type of stimulus was also not significant (F [1, 40]=1.96, p=.169, r=.22).

Discussion

Experiment 1 explored implicit learning processes in children with DD when presented with non-linguistic visual material. If children with DD have a general deficit related to implicitly learning positional rules, they would be expected to show lower levels of learning when compared to their age-matched controls. However, no differences in the performance of the two groups were found, thus suggesting that the implicit learning was similar in both groups.

Nevertheless, although children with DD performed above chance level in the seen condition, they were at chance level in the unseen condition. This latter result might suggest that transferring the underlying positional rules to new instances was somewhat challenging for participants with DD. However, the non-significant interaction in the ANOVA does not support the idea that unseen items were more difficult for the DD group compared to the TD group. Additionally, the effect size of the interaction was small (r=.22) and a power calculation tool (Faul, Erdfelder, Lang, & Buchner, 2007) revealed that more than 80 children would be needed in each group to find a significant difference for this magnitude of effect. Thus, rather than being a lack of power, we believe that this result represents a genuine lack of difference between the two groups for the stimuli used in this experiment.

As noted in the introduction, the question about an implicit learning deficit in individuals with DD should not be considered in an all-or-none fashion, but in relation to the characteristics of the learning task. Previous literature in this area has mainly focused on non-linguistic visual regularities and thus the hypothesis of an implicit learning deficit was explored in a general domain. In contrast, by introducing letters within the stimuli, experiment 2 allowed us to investigate the possible existence of a linguistic specific problem with respect to the acquisition of positional regularities.

Experiment 2: implicit learning task with linguistic content

Method

Participants. A new sample of 66 poor readers was preselected by teachers and tested as candidates for the DD group. A final sample of 21 participants with DD (12 boys and 9 girls) was selected and matched with 21 control subjects, applying the same criteria as used in experiment 1. A summary of the two groups' non-verbal IQ and reading abilities is presented in Table 2.

Materials and apparatus

Word and pseudoword reading and intelligence The same tasks used in experiment 1 to assess word and pseudoword reading as well as non-verbal IQ were used in experiment 2.

Implicit learning of orthographic regularities The design of experiment 2 was the same design used in experiment 1, with letters replacing the shapes. Thus, what follows are the details of constructing the stimuli from letters known to the children, maintaining identical positional constraints to those in experiment 1.

Stimuli were pseudowords in the form $C_1V_1C_2V_2$ and were formed from a set of 10 letters: 6 consonants (F, L, M, N, S, T) and 4 vowels (A, E, I, O). In the first consonant position (C_1), only three letters (L, M, T) could be embedded, whereas in the second consonant position (C_2), three different letters (F, N, S) could appear. No restrictions were placed on either vowel position. Thus, there were 144 possible combinations ($3\times4\times3\times4$) and these were termed *legal* as they adhered to the orthographic rules (e.g., MIFO). Thirty-six legal items were selected for inclusion in the exposure phase. Twelve of the 36 training items were selected for inclusion in a later test phase as legal seen stimuli (see "Procedure"). Another set of 12 legal items, not used in the exposure phase, was selected from the remaining 108 possible legal combinations to be used as legal unseen stimuli. None of the items were real words in Spanish.

Table 2 Mean scores and (standard deviations) of non-verbal IQ, word reading accuracy and reading speed, and pseudoword reading accuracy and reading speed broken down by group developmental dyslexia (DD) and typically developing (TD)

Group	Non-verbal IQ	Word reading accuracy	Word reading speed	Pseudoword reading accuracy	Pseudoword reading speed
DD	100.0 (8.9)	10.9 (3.4)	15.9 (13.4)	12.1 (4.6)	27.1 (21.1)
TD	100.5 (9.2)	82.6 (8.0)	84.2 (10.8)	79.0 (7.3)	85.5 (5.7)

All 24 legal stimuli (12 seen and 12 unseen) were used to generate 24 illegal stimuli. This was done by exchanging the position of C_1 and C_2 in each instance (e.g., FIMO generated from MIFO). For each participant, 16 of the possible 24 legal stimuli (8 seen and 8 unseen), along with their matching illegal stimuli, were selected for inclusion in the test phase. These 16 legal items were then randomly combined with the 16 illegal items to form 16 pairs. In the test phase, each pair was shown twice to give a total of 32 test trials for each subject, with the position of the legal items counterbalanced (left vs right). Further details about the design of this implicit learning task can be found in Nigro et al. (2015).

Explicit knowledge The acquisition of conscious knowledge about the positional rules was assessed using the same questionnaire as in experiment 1.

Results

All participants were retained for analyses as none showed evidence of explicit knowledge about the orthographic rules when answering the explicit learning questionnaire. Independent-sample *t*-tests confirmed no significant difference between the two groups in terms of non-verbal IQ (t_{40}=1.70, p=.866, r=.26). In contrast, significant differences were found for word reading accuracy (t_{40}=37.73, p<.001, r=.98), word reading speed (t_{40}=18.25, p<.001, r=.94), pseudoword reading accuracy (t_{40}=35.91, p<.001, r=.98) and pseudoword reading speed (t_{40}=12.21, p<.001, r=.89).

Figure 2 summarises the average correct response rate in the test phase for all items (32), seen items (16) and unseen items (16) separately for the DD and the TD group. In the DD group, 15 participants (71.4 %) performed above chance level, whereas in the TD group, 16 participants (76.2 %) did so.

No significant differences were found between the performance of participants across block 1 or 2 (p>.05) for either group; results were collapsed across blocks in all subsequent analyses. Results from single-sample *t*-tests showed that participants from the TD group again performed above chance level in all three cases (overall: M=63.09, SD=14.78, t20=4.06, p=.001, r=.67; seen items: M=62.20, SD=18.38, t_{20}=3.04, p=.006, r=.56; unseen items: *63*.99, SD=18.84, t_{20}=3.40, p=.003, r=.60). Of note, overall performance was very similar to that found in a previous study (Nigro et al., 2015), thus suggesting that the task evokes similar levels of implicit learning with similar samples. Participants with DD also performed above chance level in the overall task (M=57.29, SD=10.88, t_{20}=3.07, p=.006, r=.57). When seen and unseen items were analysed separately, performance on seen items was significantly above chance (M=58.63, SD=13.62, t_{20}=2.90, p=.009, r=.54), while performance on the unseen items just failed to reach significance (M=55.95, SD=13.62, t_{20}=2.00, p=.059, r=.41).

To assess whether differences between the DD and the TD group were significant, a mixed ANOVA was run. There was no main effect of group (F [1, 40]=2.10, p=.155, r=.22) nor type of legal stimulus (F [1, 40]=.02, p=.884, r=.02). The interaction between group and type of legal stimulus was also not significant (F [1, 40]=.53, p=.468, r=.11). This indicates that despite TD children showing higher scores in the experiment, the differences between the two groups were not significant. The small effect sizes again suggest that the null results are not due to a lack of statistical power and instead represent a true lack of difference between the two groups on this task.

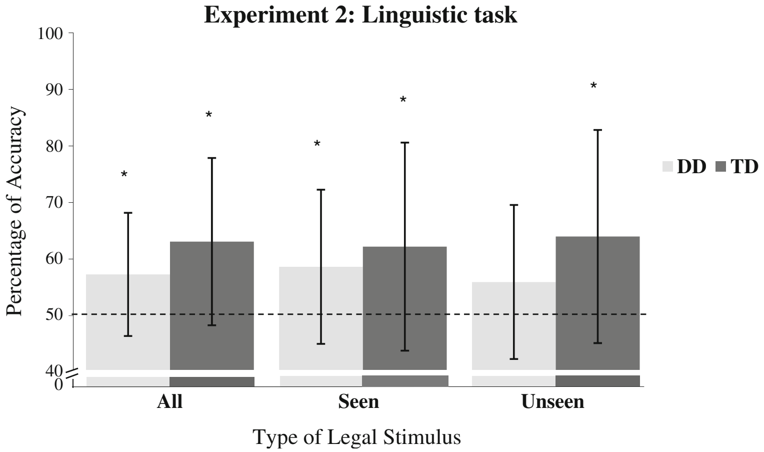

Fig. 2 Participants' mean accuracy for all, seen and unseen items, separately for the developmental dyslexia (DD) and the typically developing (TD) groups. *Error bars* represent ±1 standard deviation from the mean. An *asterisk* indicates performance significantly above chance (*dashed line*)

Discussion

Experiment 2 explored the ability of children with DD to implicitly learn linguistic regularities embedded in pseudowords with a frequent word structure (CVCV). As subjects with DD show persistent difficulties mastering orthographic patterns, we predicted that they would show an implicit learning impairment compared to TD children. However, despite including linguistic information, the pattern of results for experiment 2 was the same as for experiment 1. We found that participants with DD performed above chance level in the overall task. When seen and unseen items were analysed separately, results showed that DD children could identify items previously encountered at a significant level and that recognition of novel items approached significance.

The analysis of the variance (ANOVA) yielded no significant differences between the DD and the TD group. Taken together, the results of the *t* test and the ANOVA suggest that children with DD are able to implicitly learn simple orthographic patterns after a brief exposure in a similar manner to TD children.

Combining experiments 1 and 2

Although the regularities introduced in both experiments were identical in terms of position within the string and frequency of occurrence, they differed in terms of content (non-linguistic or linguistic). In order to determine if the presence of linguistic material moderated the learning effect, results from experiments 1 and 2 were combined into a single dataset to allow this issue to be explored.

Results

Firstly, independent-sample *t*-tests were conducted to ensure that there were no differences in the non-verbal IQ and reading performance of the two DD groups and the two TD groups across experiments 1 and 2. No significant differences were found between the two DD groups

(IQ: t_{40}=1.35, p=.186, r=.21; word reading accuracy: t_{40}=.86, p=.396, r=.13; word reading speed: t_{40}=1.72; p=.094, r=.26; pseudoword reading accuracy: t_{40}=.00, p=1.00, r=.00; pseudoword reading speed: t_{40}=1.29, p=.203, r=.20). When comparing the two TD groups, no significant differences were found regarding IQ (t_{40}=.77, p=.445, r=.12) or reading speed (word reading speed: t_{40}=.51, p=.614, r=.08; pseudoword reading speed: $t_{23.62}$=1.91, p=.069, r=.29), although significant differences were found in accuracy reading scores (word reading accuracy: $t2_{9.88}$=2.31, p=.026, r=.39; pseudoword reading accuracy: t_{40}=3.26, p=.002, r=.46) indicating that participants in the TD group of experiment 2 were better decoders than TD participants of experiment 1. Despite these differences, participants of experiment 1 were equally useful for comparison with the DD group as they all fulfilled the criteria to be classified as good readers (see "Participants").

In order to compare the performance of the DD and the TD groups across both experiments, a three-way mixed ANOVA was performed. Two of the factors were between subjects: experiment (non-linguistic or linguistic) and group (DD or TD). The remaining factor was within subjects and corresponded to type of legal stimulus (seen or unseen). Unsurprisingly, given the results from the first two experiments, neither the main effect of group (F [1, 80]=2.43, p=.123, r=.17) nor the main effect of type of legal stimulus (F [1, 80]=.03, p=.852, r=.02) were significant. Importantly, there was no main effect of type of experiment (F [1, 80]=.94, p=.335, r=.11), showing that the performance of all children as a single group was not different when learning non-linguistic or linguistic positional rules. The interaction between experiment and group (F [1, 80]=.54, p=.464, r=.08) was not significant, confirming that both DD and TD children performed equally well when presented with non-linguistic and linguistic material. Given these results, it is unsurprising that none of the other interactions reached significance: type of legal stimulus and type of experiment (F [1, 80]=.00, p=.970, r=.00); type of legal stimulus and group (F [1, 80]=2.13, p=.148, r=.16); the three-way interaction between type of stimulus, group and experiment (F [1, 80]=.11, p=.737, r=.04).

General discussion

Implicit learning mechanisms seem important to develop a set of literacy skills that can only emerge after extended periods of exposure to print (Grabe, 2010). As subjects with DD have persistent difficulties mastering written regularities, an increasing number of authors have suggested the existence of an underlying implicit learning deficit (in addition to a core phonological deficit) and this hypothesis has been approached through different paradigms. Although the existence of impaired implicit learning may be supported by a relevant number of studies (e.g., Du & Kelly, 2013; Howard et al., 2006; Jiménez-Fernández et al., 2011; Pavlidou et al., 2009; Pavlidou et al., 2010; Stoodley et al., 2008; Vicari et al., 2003), other studies found implicit learning abilities comparable to control participants (Kelly et al., 2002; Menghini et al., 2010; Pothos & Kirk, 2004; Roodenrys & Dunn, 2008). Such different patterns of results could be explained by methodological differences among studies (Lum et al., 2013). Thus, the literature suggests that implicit learning abilities should not be considered in an all-or-none fashion, but in relation to the complexities of the learning task and the characteristics of the participants.

Despite the fact that subjects with dyslexia show difficulties when processing written language, research carried out with SRT and AGL tasks have mainly focused on the implicit acquisition of non-linguistic regularities. In the present study, to our knowledge, we explored for the first time the ability of children with DD to implicitly acquire both non-linguistic and linguistic regularities after a brief exposure. In experiment 1, positional regularities were embedded in abstract shape strings, while in experiment 2, the same regularities were embedded in letter strings.

Despite using different visual materials, results from both experiments showed a very similar pattern. Participants with DD could significantly learn the positional rules; however, unlike TD children, the identification of novel legal items did not reach a significant level, suggesting that the application or transfer of this knowledge was somewhat challenging for children with DD. Nevertheless, the analysis of the variance (ANOVA) yielded no significant differences between the DD and the TD group in any of the experiments. Thus, these results indicate (i) that Spanish children with DD are able to learn positional regularities after a brief exposure similarly to non-dyslexic children and (ii) that the linguistic component does not influence per se the implicit learning of DD or TD children. The latter finding partially agrees with the work of Ise et al. (2012), who showed that the performance of German children with poor spelling skills did not differ between readable or non-readable stimuli. However, unlike Ise et al., the present study did not find a linguistic material advantage in the TD group. These contrasting results may be explained by the fact that the AGL task used by Ise et al. contained more complex regularities than the tasks of the current study.

Findings from the current study also disagree with previous research carried out with AGL tasks in dyslexic populations. Whereas the current study shows that both Spanish-speaking DD and TD children are able to implicitly acquire positional regularities, Pothos and Kirk (2004) reported that dyslexic adults outperformed non-dyslexic individuals who failed to learn the rules of an AGL task. In order to understand these differences, the characteristics of each study should be taken into account. The dyslexic participants recruited by Pothos and Kirk were adults and as such these participants may have developed compensatory strategies throughout their lives to process visual information. Furthermore, Pothos and Kirk did not apply strict criteria of dyslexia, since neither mother tongue nor intelligence was controlled. Also of note, Pothos and Kirk explained the superior performance of their dyslexic participants by suggesting that the method of presentation (namely, strings of geometric shapes presented side-by-side) caused their control subjects to exert conscious efforts to process each element of the stimuli, and that this might have interfered with their ability to implicitly learn the relationships between the elements. However, the items in the present study (both in experiments 1 and 2) were presented in the same manner and yet, TD children demonstrated significant implicit learning. Thus, the current results not only disagree with the anomalous result reported by Pothos and Kirk (superior performance by DD participants), but they also provide some evidence which weighs against the explanation provided by the authors.

Our findings also do not corroborate the existence of an implicit learning impairment in children with DD, as found by Pavlidou et al. (2009, 2010) who evaluated English-speaking children using the same AGL task as Pothos and Kirk (2004). Once again, differences in the methodology could explain the different results. Whereas

AGL tasks assess the learning of complex succession patterns, the present study assessed the learning of simple positional regularities which could have been somewhat easier for DD children to acquire. Such contrasting results suggest that IL mechanisms do not operate in an all-or-none fashion, but instead are sensitive to the nature of the learning material and, in particular, the complexity of the relationships.

In the present study, both experiments included positional rules where the identification of just position 1 or 3 was enough to successfully complete the task. Results from the ANOVA showed that children with DD were not impaired in the acquisition of these simple rules, regardless of the content (non-linguistic or linguistic). However, results from the *t*-tests suggested a trend by which children with DD could find it slightly harder to transfer these rules to new instances. Thus, this disagreement in the results suggest a main limitation in the current study: the low complexity of the material used in the implicit learning tasks may not have been demanding enough to uncover a learning impairment in the group with DD. To overcome this limitation, it would be necessary to increase the demands of the experimental tasks. Accordingly, a follow-up study should include stimuli with more complex regularities to encourage higher levels of item processing. For instance, contextual regularities could be embedded in the strings in order to study dyslexics' ability to process whole stimulus and establish connections among its parts. Specifying which regularities individuals can or cannot acquire through implicit mechanisms is important given that such mechanisms do not operate in an absolute manner. Such studies would provide useful information to plan intervention programmes. If an implicit learning deficit is corroborated when dyslexic individuals are presented with complex orthographic patterns, it might be the case that these difficulties can be compensated by explicit strategies. Thus, the contribution of implicit versus explicit teaching methods should also be explored.

Although the current study was conducted in Spanish (a transparent writing system), we believe that these findings could be generalised to other languages. Results suggest that the implicit acquisition of positional patterns is a relatively simple task for third graders and it is not affected by the linguistic content of the items. Thus, based on the present results, we would not expect dyslexic children who spoke a more opaque language (such as English) to demonstrate learning difficulties on this task.

To summarise, the present study explored for the first time the ability of children with DD to implicitly learn positional rules embedded in both non-linguistic and linguistic strings. Both the DD group and the TD group were able to acquire the positional rules regardless of the nature of the material, with no differences found between the two groups. Nevertheless, within group analyses showed that the DD group found it somewhat difficult to generalise the rules to novel stimuli. Thus, although no implicit learning impairment was found in the DD group, it may be the case that more complex regularities would prove more difficult to acquire through implicit mechanisms. Thus, our findings encourage further investigation regarding the possibility that an underlying implicit learning deficit may play a role in dyslexia.

Acknowledgments This research has been partially supported by PITN-215961-ELDEL project of the FP7 Marie Curie programme and HUM-820 research group of the Junta de Andalucía.

Appendix

Table 3 Abstract shapes used in experiment 1 and letters used in experiment 2

Experiment 1	Experiment 2
	A
	E
	I
	O
	D
	F
	L
	M
	N
	S
	T

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