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A lab-controlled simulation of a letter–speech sound binding deficit in dyslexia

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ABSTRACT

Dyslexic and non-dyslexic readers engaged in a short training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. We examined whether a letter–speech sound binding deficit is behaviorally detectable within the initial steps of learning a novel script. Both letter knowledge and word reading ability within the artificial script were assessed. An additional goal was to investigate the influence of instructional approach on the initial learning of letter–speech sound correspondences. We assigned children from both groups to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction is followed by implicit learning. Our results indicated that dyslexics were outperformed by the controls on a time-pressured binding task and a word reading task within the artificial orthography, providing empirical support for the view that a letter–speech sound binding deficit is a key factor in dyslexia. A combination of explicit instruction and implicit techniques proved to be a more powerful tool in the initial teaching of letter–sound correspondences than implicit training alone.

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Introduction

Developmental dyslexia, hereafter referred to as dyslexia, is commonly diagnosed when people unexpectedly and persistently fail to develop fluent reading skills (Fletcher & Lyon, 2008). Prevalence estimates of dyslexia typically range from 3% to 10% of the population, depending on the precise criteria used for its assessment (Snowling, 2013). The exact nature is still under debate, but the most commonly accepted hypothesis is that dyslexia is a language-based disorder that stems from a deficit in the phonological processing system (Dehaene, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). A subtle neurological defect that is associated with a genetic predisposition is assumed to be the underlying factor (Dehaene, 2009; Pennington & Olson, 2005; Richlan, Kronbichler, & Wimmer, 2009).

According to the phonological theory of dyslexia, a specific deficit in the representation, storage, and retrieval of speech sounds hinders the ability to attend to and manipulate them (Mattingly, 1972; Vellutino et al., 2004). Because this so-called phonological awareness is assumed to be an essential prerequisite for becoming literate, a lack of it complicates the acquisition of reading and spelling skills. However, the phonological deficit in dyslexia is not restricted to a lack of phonological awareness. Dyslexia is also characterized by disrupted rapid automatized naming of visually presented material (Denckla & Rudel, 1976; Norton & Wolf, 2012). In fact, low achievement on a task of naming a series of familiar items as quickly as possible seems to be one of the strongest predictors of dyslexia (see Norton & Wolf, 2012, for a review). The extent to which rapid naming problems are independent of other phonological problems is still debated (e.g., Vaessen, Gerretsen, & Blomert, 2009), but cross-cultural studies confirm that a combination of deficits in phonological awareness and rapid naming results in the most severely impaired reading skills (Norton & Wolf, 2012; Papadopoulos, Georgiou, & Kendeou, 2009).

A third factor that has been identified as characteristic of dyslexia, and that has often been included under the umbrella of the phonological deficit, is poor verbal short-term memory (Mann & Liberman, 1984; Wagner & Muse, 2012). Typically, findings indicate that poor readers have shorter verbal memory spans on digit span tasks and nonword repetition tasks.

An important assumption of the phonological theory of dyslexia is that the phonological impairments hinder the establishment of proper letter–speech sound mappings, which is the foundation of reading alphabetic languages, resulting in disfluent word recognition. Thus, the theory provides a straightforward link between the underlying cognitive problem and the behavioral manifestation.

Despite its presumed importance as a link between a phonological deficit and the reading failure that characterizes dyslexia, letter–speech sound binding has long received little attention from an empirical point of view. A dearth of research that has been counterbalanced by an increasing number of studies published during recent years (e.g., Blau et al., 2010; Blomert & Vaessen, 2009; Brem et al., 2010; Froyen, Bonte, Van Attevelde, & Blomert, 2009). In the current study, we aimed to contribute to this emerging literature by experimentally manipulating the learning of letter–speech sound associations in normal and dyslexic readers.

Letter–speech sound mapping

In relatively transparent orthographies, such as Dutch, most children acquire the knowledge of letter–speech sound associations within approximately 1 year of formal reading instruction (Blomert & Vaessen, 2009). However, several more years of instruction and practice are needed for these associations to become fully automated (Blomert & Vaessen, 2009; Froyen et al., 2009). This process, in which learned associations between phonemes and graphemes become integrated into newly constructed audiovisual units, has been referred to as letter–speech sound binding (Blomert, 2011).

Using a mismatch negativity paradigm, Froyen et al. (2009) demonstrated that after 1 year of reading instruction, beginning readers did not show any early neural signs of letter–speech sound integration. Moreover, they found that even after 4 years of reading instruction, the integration was still not “adult-like.”

In addition, in measuring response latencies of letter–speech sound matching, Blomert and Vaessen (2009) showed that processing speed of these associations increased systematically over the full range of primary school grades despite ceiling performance on accuracy measures from first grade onward. A comparison between normal readers and poor readers indicated that normal readers outperformed poor readers on accuracy measures only during the first 2 years of reading instruction. On speed measures, the performance of normal readers was superior in all grades. Moreover, their response latencies decreased steadily until Grade 6. In contrast, the response latencies of dyslexic readers did not improve anymore from Grade 5 onward.

Direct evidence for disrupted letter–speech sound learning in dyslexia comes mainly from neuro-imaging research. It has been demonstrated that the activity of the superior temporal sulcus is strongly associated with the neural integration of letter–speech sound pairs (Blau, Van Atteveldt, Formisano, Goebel, & Blomert, 2008; Hashimoto & Sakai, 2004; Van Atteveldt, Formisano, Goebel, & Blomert, 2004). Imaging studies revealed that in dyslexia, the activity in this region in response to letter–speech sound associations is reduced in both children and adults (Blau, Van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Blau et al., 2010).

Interestingly, Blomert and Willems (2010) found that a letter–speech sound learning problem was already present in preschool children at familial risk for dyslexia. These at-risk children did not gain from a 10-week letter–speech sound training, whereas the controls improved significantly. This indicates that although the neural integration of letter–speech sound associations is a gradual process that takes many years to fulfill, differences between dyslexic and normal readers can potentially be detected during an initial phase.

Instructional approach

Besides the wiring in the brain, reading proficiency also depends on the quality of the instruction given. Therefore, we included instructional approach as a factor in our study as well. It has been demonstrated convincingly that manipulations of educational approaches to teaching reading skill can have a substantial impact on learning outcome and on related changes in the brain (McCandliss, 2010).

In the case of dyslexia, extensive literature indicates that specialized intervention is effective in ameliorating reading and spelling proficiency and that the most effective treatment programs include (a) phonetic awareness training, (b) systematic and explicit instruction of letter–speech sound mappings, and (c) rule-based or strategy training for mastering letter–speech sound inconsistencies in words (see Singleton, 2009, for an overview). Despite the positive results of specialized intervention, it should be noted that reading rate is less susceptible to improvement than reading accuracy (Morris et al., 2012; Singleton, 2009).

Driven by the quest for new fluency-oriented remediating methods and by the knowledge from recent brain research, there is a current tendency to exchange traditional explicit techniques for implicit techniques, which are based mainly on associative learning and massive exposure and which make use of a computer game environment (Aravena & Tijms, 2009; Lovio, Halttunen, Lyytinen, Näättänen, & Kujala, 2012; Lyytinen, 2008; Saine, Lerkkanen, Ahonen, Tolvanen, & Lyytinen, 2011). These techniques, which are particularly useful for letter–speech sound training, are implicit in the sense that learning is established not by instruction but rather by complying with the game objectives, which obviously coincide with educational aspirations.

Although implicit learning plays an important role in learning to read (Gombert, 2003; Sperling, Lu, & Manis, 2004) and implicit associative techniques are promising in refining dyslexia intervention (Aravena & Tijms, 2009; Lovio et al., 2012; Lyytinen, 2008; Saine et al., 2011), we need to be cautious of throwing the baby out with the bathwater by abandoning explicit instruction. It is assumed that the development of explicit and systematic decoding skills acts as a bootstrapping mechanism for further implicit learning (Aravena & Tijms, 2009; Gombert, 2003; Share, 1995). This idea is supported by more general accounts of skill acquisition in which controlled metacognitive processing typical of novice performance is gradually being replaced by automatic associative processes with growing expertise (Chein & Schneider, 2005; Siegler, 2005).

Clinical evidence for the interplay between initial explicit and subsequent implicit processes comes from research by Tijms (2007). His data revealed that during the first half of traditional dyslexia inter-

vention, most progress was made on reading accuracy, which gradually turned over into a more prominent development of reading rate during the second half of intervention. Moreover, in contrast to reading accuracy, reading rate continued to develop after termination of the intervention.

The current study

In our study, dyslexic and non-dyslexic readers engaged in a short training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. The script was artificial in the sense that unfamiliar letters (Hebrew) were used to transcribe participants' native language (Dutch). By this means, we were able to compare the initial steps of dyslexic and non-dyslexic readers in learning a novel script. If dyslexics have a deficit for learning letter–speech sound associations, we would expect them to be at a disadvantage right from the start when getting familiar with a new set of letter–speech sound correspondences.

One advantage of adopting an artificial script is that it allows for precise control over the input. Differences in previous exposure to experimental stimuli can be ruled out, allaying concerns about noncontrolled factors influencing performance. Hence, the artificial script paradigm is especially useful for exploring phenomena associated with the early phases of learning to read in children that are already literate to some extent.

In contrast to previous behavioral studies that yielded evidence for deficits in letter–speech sound learning in dyslexia, such as the aforementioned studies by Blomert and Vaessen (2009) and Blomert and Willems (2010), in the current study we were able to control completely for differences in exposure to the concerned letter–speech sound correspondences. Moreover, by using the artificial script, we were able to study letter–speech sound learning in dyslexic readers at different ages, taking away the necessity of using preliterate children at familial risk for dyslexia. Thus, an artificial script provides a powerful tool for studying letter–speech sound learning in dyslexics and for extending the literature on the etiology of dyslexia.

Only a few studies have addressed letter–speech sound learning within an alphabetic artificial orthography (Hashimoto & Sakai, 2004; Maurer, Blau, Yoncheva, & McCandliss, 2010; Taylor, Plunkett, & Nation, 2010; Yoncheva, Blau, Maurer, & McCandliss, 2010). To our knowledge, the current study is the first to focus on letter–speech sound learning within an artificial orthography with dyslexic readers.

To evaluate the influence of an instructional approach, we assigned children from both groups to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction is followed by implicit learning. Both letter knowledge and word reading ability within the artificial script were assessed during the training session.

Most writing systems also include nonstandard letter–speech sound correspondences, producing spelling patterns that depend on syllabic, morphological, or syntactic structure. To master these correspondences, children are taught explicit spelling rules at school, although there is evidence that beginning readers also capitalize on implicit mechanisms while learning spelling rules (Cassar & Treiman, 1997; Kemp & Bryant, 2003; Pacton, Perruchet, Fayol, & Cleeremans, 2001; Wright & Ehri, 2007). For example, Cassar and Treiman (1997) found that young children had knowledge of which letters can be doubled in English without being taught the corresponding rule.

To capture the characteristics of natural language, we also included a spelling rule in the artificial orthography. We were interested to see whether there are signs of implicit learning of nonstandard correspondences within the initial steps of learning a novel script.

Because the current study uses an artificial script paradigm, findings can have practical implications only if we can translate them to reading skills in the real world. Therefore, we also examined whether reading proficiency in the trained script correlated with the typical reading skills learned at school.

In summary, in the current study, we examined whether disrupted letter–speech sound learning is behaviorally detectable within the initial steps of learning a novel script and whether there are differences between dyslexic readers and the controls in the ability to read the novel script after a short letter–speech sound training. In addition, we assessed whether differences in instructional approach

lead to differences in learning outcome. Finally, we evaluated the validity of our results by correlating reading proficiency in the trained novel script with reading proficiency in the orthography belonging to the native language.

Methods

Participants

Our sample consisted of 62 children (35 boys and 27 girls) diagnosed with dyslexia and 64 children (31 boys and 33 girls) with average or above average reading and spelling skills. The children diagnosed with dyslexia were recruited from the IWAL Institute, a nationwide center for dyslexia in The Netherlands. The nonimpaired readers were selected from the same sample of schools as the dyslexic readers to control for socioeconomic status (SES), demography, and education. The age range spanned from 7.5 to 12.4 years. All participants were primary education pupils and were native speakers of Dutch. We obtained informed consent from all of the parents involved. The study was approved by the ethics committee of the University of Amsterdam. Participant characteristics are shown in Table 1. No significant baseline differences in age, intelligence, or vocabulary were found between the two reading groups (all $ps > .05$).

Selection criteria

Selection of the dyslexic group was based on criteria for severe dyslexia in the Dutch health care system (Blomert, 2006), implying that children had a severe and persisting reading problem in combination with a phonological deficit. Inclusion of a causal factor provides the possibility to select a homogeneous sample, making generalization and replication of results possible (Torgesen et al., 1999). More specific, children were selected for the study if they met all of the following three inclusion criteria: (a) either word reading rate of 1.5 standard deviations or more below average or word reading rate of at least one standard deviation below average together with a spelling skill of 1.5 standard deviations or more below average, (b) performance on at least two of six administered phonological tasks (i.e., grapheme–phoneme identification task accuracy and speed, phoneme deletion accuracy and speed, and rapid naming of numbers and letters) that was at least 1.5 standard deviations below average; and (c) poor response to intervention provided at school. Exclusion criteria were uncorrected sensory disabilities, broad neurological deficits, insufficient education, and attention deficit/hyperactivity disorder (ADHD). Because we incorporated Hebrew graphemes into our artificial orthography, previous experience with Hebrew script was also an exclusionary criterion.

Allocation to the control group was based on the school record. We selected normal achieving children within general education. Children were selected only if both their reading and spelling scores were above the 25th percentile.

Table 1
Participant characteristics by reading group and training condition.

	Dyslexic ($n = 62$)						Control ($n = 64$)					
	EXP ($n = 21$)		IMP ($n = 21$)		COM ($n = 20$)		EXP ($n = 20$)		IMP ($n = 21$)		COM ($n = 23$)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Age	9.79	1.02	9.71	1.05	9.65	.83	9.77	.78	9.89	1.19	9.95	1.00
IQ	6.81	2.04	6.53	2.00	6.47	1.68	7.30	2.08	6.95	1.88	7.26	2.09
Vocabulary	6.10	1.18	6.05	1.69	5.85	1.66	6.40	1.19	6.05	1.28	6.91	1.44

Note. EXP, explicit condition; IMP, implicit condition; COM, combined condition.

Artificial orthography

The artificial orthography consists of eight Hebrew graphemes that are randomly matched to Dutch phonemes, thereby providing eight basic letter–speech sound pairs. Because evidence exists that letter shapes are not an arbitrary cultural choice but rather a product of our neural architecture (Dehaene, 2009, p. 173), we adopted Hebrew script to capture the characteristics of graphemes as they naturally occur.

The script represents four vocals and five consonants. Combinations of phonemes producing strong coarticulation effects were avoided. Table 2 displays an overview of the letter–speech sound correspondences that were used. The directionality of the script is left to right.

From the corpus of words that could be created by combining the nine chosen phonemes, we selected 116 high-frequent Dutch monosyllabic words of which 86 words were used for training purposes. The remaining 30 words were used for the word reading assessment. Thus, by using other words for training purposes rather than for assessment, the current study was designed to find transfer of learning by ruling out the possibility that words from the training were recognized without decoding.

We composed an additional set of 52 pseudowords that were also used for training purposes. All pseudowords obeyed Dutch phonotactic regularities.

One letter (ד) in our artificial orthography was ambiguous because it corresponded with both the short vowel /α/ and the long vowel /a/. Correct interpretation of this letter could be obtained only by applying the following rules:

- A short vowel /α/ is followed by a consonant that is written with a single grapheme (דא).
- A long vowel /a/ is followed by a consonant that is written with a double grapheme (דאא).

Training methods

Children in both groups participated in a single session, during which two 30-min training blocks (A and B) were employed for either explicit or implicit training. Both training approaches are outlined below.

Explicit instruction approach

The explicit training we developed was based on specialized dyslexia treatment as it is employed in clinical practice nowadays (see Singleton, 2009, for an overview), implying that all exercises were aimed at systematic instruction of phonological structure and letter–speech sound mapping combined with rule-based training for mastering letter–speech sound inconsistencies in words. We provided the trainer with a protocol to ensure standardization of instruction.

At the start of Block A, children were told that they were engaging in a task where they would be learning a secret code. During the training, we used software containing several exercises designed to give pupils explicit insight into the way letters and speech sounds correspond. The exercises were guided by the experimenter's verbal instruction. First, all letter–speech sound correspondences were introduced one by one. To support retention, speech sounds were linked to words, which in turn were represented by images. In Fig. 1, for example, the letter ד is matched with the speech sound /r/ and is supported by an image of the Dutch word *roos* ('rose') that starts with /r/.

Subsequently, children needed to compose words dictated by the experimenter using a small keyboard displayed on the screen. On a keystroke, the corresponding sound was presented simultaneously through a speaker. The arrangement of the keyboard differed with every item to avoid

Table 2
Letter–speech sound correspondences within an artificial orthography.

Letter	א	ב	ד	ה	ו	ז	ח	ט
Speech sound (IPA)	[u]	[ε]	[α] [a]	[k]	[r]	[l]	[t]	[n]

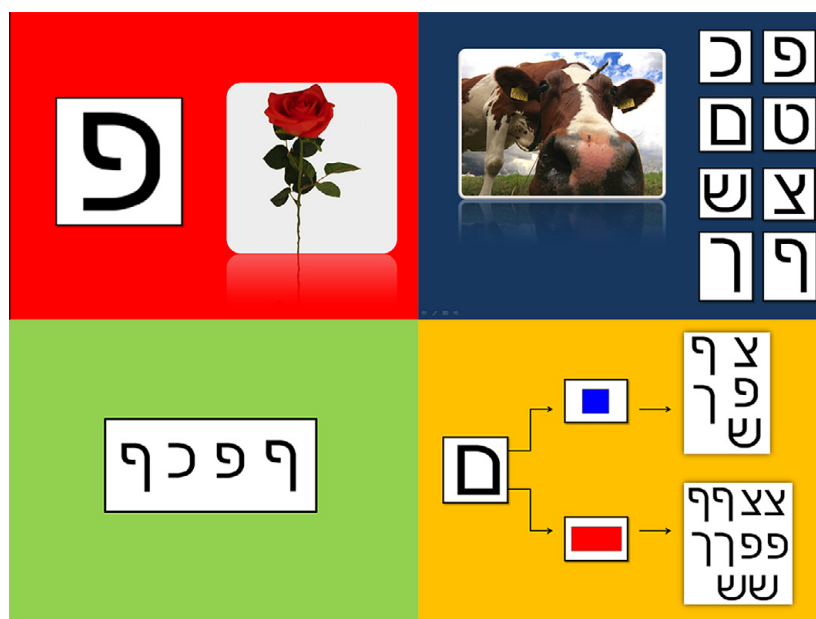


Fig. 1. Screenshots from explicit training.

spatial learning. Fig. 1 depicts an example of this exercise in which the stimulus is the Dutch word *koe* ('cow').

Finally, children were presented with a sequence of letters and needed to blend the corresponding speech sounds to form words (Fig. 1).

After approximately 20 min, the experimenter presented the orthographic rule with the aid of the plan displayed in Fig. 1. During the remainder of the block, exercises that contained words both with and without the rule were repeated.

In contrast to the associative training condition in which fast playing was encouraged, there was no time pressure during explicit instruction.

Block B of the explicit training contained similar exercises as Block A. No additional instruction was given. In contrast to Block A, Block B also included pseudowords. Three additional exercises were introduced in Block B: an exercise with shuffled letters that needed to be rearranged into words, an exercise in which all letters were fading away while children needed to recall the position in response to a presented speech sound, and a memory span exercise in which children needed to repeat back orally a progressively larger sequence of letters. Although some of the exercises in Block B had limited stimulus exposure, response time again was unlimited.

Associative instruction approach

For the implicit associative training, we employed a computer game in which children needed to match speech sounds to their corresponding orthographic representations. Correct associations led to success in the game, whereas incorrect associations jeopardized a positive outcome. Fast playing was reinforced by progressive time restrictions and by providing bonuses for fast playing. More specific, children operated a cannon at the bottom of the screen, moving it horizontally. The upper part of the screen was composed of columns of balloons containing single letters or words. Children were required to act on speech sounds that were presented repeatedly in the game. The response consisted of releasing bullets from the cannon and associating them to their corresponding orthographical representations. When children managed to clear a field of balloons, a new field was presented. Because fields became increasingly more complex and children needed to succeed in order to progress in the game, the training is adaptive in nature. Fig. 2 depicts some screenshots from the game.

At the start of Block A, children were presented with a standardized instruction that is integrated in the software. This instruction clarified the specifics of the game but did not reveal the underlying learning objective. All fields in Block A contained single-letter stimuli.

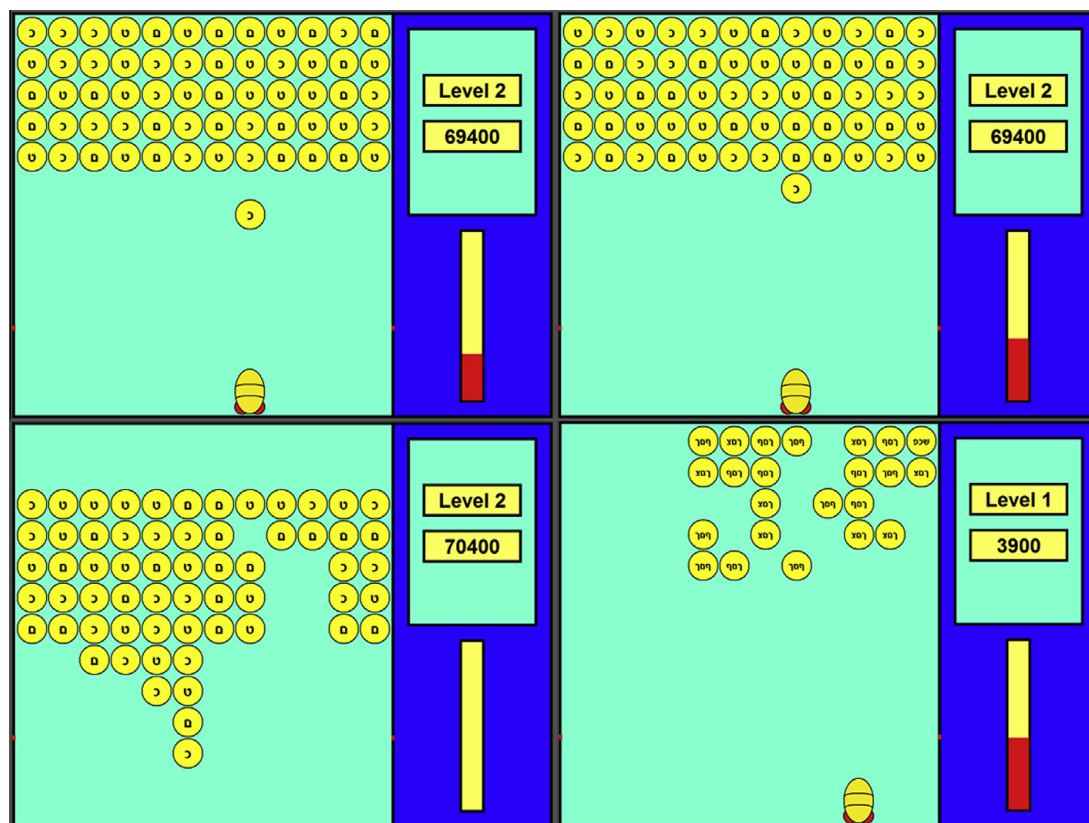


Fig. 2. Screenshots from implicit training.

In Block B, some balloons contained single letters, whereas others contained words. This change was introduced by an additional instruction at the start of Block B. In Block B, some fields included words that could be deciphered successfully only by applying the orthographical rule, giving children the opportunity to learn the rule.

After the instruction, children received a short practice trial to become familiar with the setup and the controls of the game. For children in the combined condition, this trial followed the instruction introducing Block B. During the training session, children wore headphones.

Outcome measures

We included seven outcome measures in our study. Four of them were used for assessing the effects of the training. One measure was included to relate the training effects to the actual Dutch reading skills. The two other measures were used to control for differences in general intelligence and vocabulary. An overview of the outcome measures is provided below.

Letter knowledge

We used four identical evaluation forms (EF 1–4) for assessing letter knowledge. The experimenter presented children with the form containing the eight letters. While pointing at one of the letters, the experimenter asked children to name the letter and wrote down the answer. For the retention task at home, each child's parents took over the role of the experimenter. For each of the forms, the score was determined by the number of speech sounds that were named (maximum = 9).

Error rate within computer game

The amount of errors during the implicit training was recorded automatically by the software. The score was expressed as the total number of errors divided by the total number of items. Because this

measure applies exclusively to the implicit training, data were taken only from Block B of the implicit and combined conditions.

Word reading rate in artificial orthography

We administered a lab-created time-limited test (3MAST) consisting of a list of 30 high-frequency Dutch words written within the artificial orthography. The words were presented in lowercase Arial typeface, font size 24, and arranged in two columns of equal length. Children needed to read as many words as possible within 3 min. Words were arranged with increasing complexity. The score was determined by the number of words read correctly per second.

Mastery of orthographic rule

We used a dichotomous measure based on the 3MAST reading test to assess mastery of the spelling rule. From the list of 30 words, eight words required the application of the orthographic rule for reading them correctly. When children managed to apply the rule properly in all words read within the time limit, it was considered an acknowledgment of mastery.

Word reading rate in Dutch

We used the One-Minute Test (Brus & Voeten, 1973), a time-limited test consisting of a list of 116 unrelated words of increasing difficulty, for assessing word reading skills in Dutch. The score was determined by the number of words read correctly within 1 min ($r_s = .89-.93$, test–retest).

Intelligence measure

General intelligence was assessed by the Analogies subtest from the SON-R (Snijders–Oomen Non-verbal test; Laros & Tellegen, 1991), a nonverbal reasoning-by-analogy task in which children need to extract a principle and apply it to a new situation ($r = .79$, test–retest).

Vocabulary

Vocabulary was assessed by the Vocabulary subtest from the WISC-III (Wechsler Intelligence Scale for Children; Kort et al., 2005), a measure of expressive vocabulary in which children needed to describe the meanings of words of increasing complexity ($r = .90$, test–retest).

Procedure

As mentioned before, the session consisted of three 30-min blocks; the first two blocks served as the training, whereas the third block was devoted to administering a short intelligence test and a vocabulary test. After each block, we evaluated letter knowledge by presenting children visually with the eight letters and asking them to name the corresponding sounds. This evaluation task was repeated at home 1 week after the training session to measure retention of letter knowledge. Accordingly, we instructed parents to conduct the task and to send back filled-in companion forms.

After the second evaluation of letter knowledge, when both training blocks were completed, we administered a single-word reading task containing words written in the artificial orthography. Fig. 3 depicts an overview of the entire session, including the retention measure.

BLOCK A		BLOCK B		BLOCK C		1 week interval	
30 min		30 min		30 min			
Explicit or implicit training		Explicit or implicit training		Intelligence & vocabulary assessment			
	EF1		EF2 & 3MAST		EF3		EF4

Fig. 3. Session overview. Note: EF, letter knowledge assessment within artificial script, 3MAST, reading assessment within artificial script.

All participants completed the entire session. We were able to use data from 97 of 126 filled-in companion forms for the 1-week retention measure. Data from the other 29 forms were missing due to noncompliance. For most cases of noncompliance, parents exceeded the 1-week term for administering the evaluation.

All three blocks were provided on a one-to-one basis in a silent room. The nonimpaired readers attended their session in the school building. The dyslexic readers were invited to the nearest branch of the dyslexia institute from which they were recruited. For both the explicit and implicit training, we used an Acer Aspire 5500Z 14.1-inch laptop computer in full-screen mode. The total duration of the session was approximately 100 min.

Results

Preliminary analyses with age and IQ as covariates did not change the pattern of findings reported below.

Letter–speech sound binding deficit

To determine whether a letter–speech sound binding deficit was manifest in dyslexic readers while learning a novel script, we first compared the scores of both groups on the evaluation task of letter knowledge administered at four different moments (EF 1–4: halfway training, end training, 30-min follow-up, and 1-week follow-up, respectively). We used a generalized linear model based on ordinal logistic regression consisting of group (dyslexia or control), condition (explicit, implicit, or combined), and time (EF 1, 2, 3, or 4) as factors and letter knowledge as a dependent variable. By this means, differences in learning outcome due to differences in instructional approach were taken into account within the same model. The mean scores and standard deviations obtained are shown in Table 3. Analysis revealed a significant main effect for condition, Wald chi-square = 97.34, $p < .0001$, with a medium to large effect size ($w = .45$), and for time, Wald chi-square = 33.18, $p < .0001$, with a medium effect size ($w = .26$). Importantly, the model indicated that letter knowledge was significantly lower after the associative training than after both the explicit and combined training. The time effect revealed that letter knowledge was significantly higher when assessed after Block B (end training) and Block C (30-min follow-up) than after Block A (halfway training) and the 1-week follow-up. We did not find main effects for group, Wald chi-square = .11, $p = .74$, or significant interactions between group and condition, Wald chi-square = 3.14, $p = .21$.

Thus, the results show that disrupted letter–speech sound binding was not manifested through differences in basic letter knowledge after training. The new correspondences were learned quite easily by most of the participants, and no differences were found between dyslexics and controls.

A second analysis concerned the error rate during the implicit training. Applying the knowledge of the newly learned correspondences in game play imposes much higher demands on the quality of these correspondences. Because error rate applies exclusively to the implicit training, a comparison could be made only between the implicit and combined conditions. The mean scores and standard deviations obtained are shown in Table 4. We conducted a two-way analysis of variance (ANOVA) with

Table 3
Means and standard deviations for letter knowledge.

	Dyslexic						Control					
	EXP		IMP		COM		EXP		IMP		COM	
	<i>M</i> (<i>SD</i>)	<i>n</i>	<i>M</i> (<i>SD</i>)	<i>n</i>	<i>M</i> (<i>SD</i>)	<i>n</i>	<i>M</i> (<i>SD</i>)	<i>n</i>	<i>M</i> (<i>SD</i>)	<i>n</i>	<i>M</i> (<i>SD</i>)	<i>n</i>
EF 1	8.05 (.38)	21	6.05 (1.75)	21	7.55 (.95)	20	7.85 (.49)	20	5.14 (1.49)	21	7.70 (.88)	23
EF 2	8.00 (.32)	21	6.33 (1.74)	21	7.50 (.95)	20	8.00 (.00)	20	6.29 (1.31)	21	7.91 (.67)	23
EF 3	8.00 (.00)	21	6.38 (2.01)	21	7.80 (.89)	20	8.00 (.00)	20	6.38 (1.24)	21	7.91 (.67)	23
EF 4	7.62 (.62)	16	5.94 (1.95)	16	7.30 (1.06)	10	7.81 (.40)	16	5.76 (1.15)	17	7.59 (1.05)	22

Note. EXP, explicit condition; IMP, implicit condition; COM, combined condition; EF, evaluation form.

Table 4

Means and standard deviations for error rate during training.

	Dyslexic				Control			
	EXP		IMP COM		EXP		IMP COM	
	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>
Error rate	.23 (.08)	20	.31 (.11)	20	.18 (.08)	21	.24 (.06)	23

Note. EXP, explicit condition; IMP, implicit condition.

group (two levels) and condition (two levels) as factors. Because we were dealing with proportional data with a binomial distribution, we applied an arcsine transformation to stabilize the variance. We found significant main effects for group, $F(1,80) = 10.02$, $p < .01$, with a medium to large effect size (partial $\eta^2 = .11$), and for condition, $F(1,80) = 15.54$, $p < .0001$, with a large effect size (partial $\eta^2 = .16$). In both conditions, dyslexic children made significantly more errors during training than the controls. Furthermore, both groups made fewer errors after 30 min of explicit training than after 30 min of associative training. No interaction effect was found, $F(1,80) = .07$, $p = .79$.

The results indicate that during training, when speech sounds needed to be matched to their corresponding letters under pressure of time, dyslexic children were more prone to errors than the controls. Accordingly, this finding points to an early manifestation of disrupted letter–speech sound binding.

From binding deficit to reading problems

If the higher error rate during the implicit training represents a letter–speech sound binding deficit, we also would expect dyslexics to be at a disadvantage when it comes to reading the novel script. To determine whether there were differences between dyslexic readers and the controls in the ability to read the novel script after a short letter–speech sound training, we conducted a two-way ANOVA with group (two levels) and condition (three levels) as factors. The mean scores and standard deviations obtained are shown in Table 5. Analyses revealed significant main effects for group, $F(1,120) = 7.88$, $p < .01$, with a medium effect size (partial $\eta^2 = .06$), and for condition, $F(2,120) = 51.36$, $p < .0001$, with a large effect size (partial $\eta^2 = .46$). The controls read significantly more words per second than the dyslexic children. The Helmert contrast indicated that the amount of words read per second was significantly lower after the associative training than after both the explicit and combined training ($p < .0001$). Furthermore, it showed that the amount of words read per second was also significantly lower after combined training than after explicit training ($p < .05$). No significant interaction effect was found between group and condition, $F(2,120) = 2.05$, $p = .13$.

Because letter knowledge is a basic requirement for obtaining reading proficiency, and differences in word reading could be due to differences in letter knowledge, we also conducted analyses on the sample of children who reached full mastery of the letter–speech sound associations within the artificial orthography. After 60 min of training, 71.4% of participating children (73.4% of dyslexics and 69.4% of controls) reached complete mastery of the letter–speech sound associations within the

Table 5

Means and standard deviations for reading within the artificial orthography.

	Dyslexic (<i>n</i> = 62)						Control (<i>n</i> = 64)					
	EXP		IMP		COM		EXP		IMP		COM	
	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>
WPS	.16 (.06)	21	.05 (.03)	21	.11 (.06)	20	.17 (.04)	20	.06 (.04)	21	.16 (.07)	23
WPS mastery	.16 (.06)	20	.07 (.02)	8	.14 (.04)	15	.17 (.04)	20	.12 (.02)	5	.17 (.06)	22

Note. EXP, explicit condition; IMP, implicit condition; COM, combined condition; WPS, words read per second.

artificial orthography; that is, they correctly matched all eight speech sounds to their corresponding letters (or even to nine when children spontaneously executed the rule). A Pearson's chi-square analysis showed no significant difference between the dyslexic and control groups, $\chi^2(1) = .26$, $p = .70$. Additional analyses on this sample revealed that the results are slightly more pronounced when full mastery is required. Table 5 displays means and standard deviations. Again, significant main effects were found for group, $F(1,84) = 8.20$, $p < .01$, with a medium effect size (partial $\eta^2 = .09$), and for condition, $F(2,84) = 9.43$, $p < .0001$, with a large effect size (partial $\eta^2 = .18$). Controls outperformed dyslexics on the reading task, and the Helmert contrast indicated that the amount of words read per second was significantly lower after the associative training than after both the explicit and combined training ($p < .0001$).

The current results indicate that normal readers read substantially faster than dyslexic children after just 1 h of training in the novel orthography. This finding could not be explained by differences in letter knowledge because differences between normal and dyslexic readers were also manifest when only children with complete mastery were included.

Rule knowledge

To test whether instructional approach predicted the proper application of the orthographic rule, we compared rule mastery on the 3MAST reading test after each of the three conditions. A Pearson's chi-square showed that there was a significant association between instructional approach and mastery of the orthographic rule during the reading task, $\chi^2(2) = 64.566$, $p < .01$. This seems to represent the fact that, based on the odds ratio, the odds of applying the rule were more than 100 times higher after explicit training than after associative training and were more than 20 times higher after combined training than after associative training. In fact, none of the children from the associative training condition was able to deduce the orthographical rule by himself or herself. Thus, the explicit component of the training seems to be of decisive importance for mastering the orthographic rule.

We found a small, but nonsignificant, difference in rule mastery between the dyslexics and the controls. After training, 66.1% of dyslexics and 76.6% of controls showed mastery of the orthographic rule during the reading task.

Reading in artificial orthography compared with reading in natural language

To compare reading proficiency in the trained script with the typical reading skills learned at school, we conducted a Pearson correlation (two-tailed) within the dyslexic group. Because letter knowledge is a basic requirement for obtaining reading proficiency, in the analyses we included only children who reached full mastery of the letter–speech sound associations within the artificial orthography ($N = 42$). A significant correlation was found between reading rate (words per second) in the artificial orthography and reading rate in Dutch, the natural language of the children participating in this study ($r = .52$, $p < .0001$).

This result supports the external validity of our study and thereby seems to legitimize generalizations of our main findings to reading in natural languages.

Discussion

In the current study, we focused on the initial development of letter–speech sound associations, the first crucial step in reading development. Because our study is the first to address the initial phase of letter–speech sound learning in dyslexia by using an artificial orthography, we can report several interesting findings.

Our results indicated differences between normal readers and dyslexic readers during the first stages of learning letter–speech sound correspondences, providing empirical support for the view that a letter–speech sound binding deficit is a key factor in dyslexia (Blau et al., 2009, 2010; Blomert, 2011; Blomert & Vaessen, 2009). In line with previous findings, we did not find differences in basic letter knowledge after a short training. Most of the children in both the dyslexic and control groups learned

the new correspondences relatively fast and were able to name the letters correctly. We did find evidence for disrupted letter–speech sound learning in dyslexia, however, when children needed to apply their knowledge of these correspondences in more complex tasks. When during training speech sounds needed to be matched to their corresponding letters under time pressure, the dyslexic children were more prone to errors than the controls. Moreover, controls outperformed dyslexics on a word reading task containing familiar words written in the artificial orthography. It is important to note that the differences we found between dyslexic and normal readers were independent of letter knowledge.

By adopting an artificial orthography, we were able to extend previous results with regard to some important issues. In the [Blomert and Vaessen \(2009\)](#) study, where letter–speech sound processing was explored throughout primary school, it was difficult to control for the interplay among letter–speech sound learning, phonological development, and reading development. It is possible that the normal readers outperformed the poor readers on speed measures as a consequence, rather than as a cause, of reading disabilities. In the [Blomert and Willems \(2010\)](#) study, this problem was remedied by using a sample of preliterate children at risk for dyslexia. But because training took place within the first half year of reading instruction at school, potential differences in exposure between the groups still could not be excluded. Reading circumstances could have been different for children from a family with a sibling diagnosed for dyslexia. In the current study, we were able to rule out potential differences in prior exposure to experimental stimuli and to show that dyslexics carry a binding deficit with them and that this deficit is manifested at any time when presenting them with a novel script.

An additional goal of the current study was to investigate the influence of instructional approach on the initial learning of letter–speech sound correspondences. We were specifically interested in the role of implicit training techniques because they might induce automation of letter–speech sound processing. Because children started the training without any previous knowledge of the script, and more than two thirds of them knew all correspondences afterward, the findings clearly indicated that both the explicit and implicit training we provided resulted in learning. Importantly, the implicit training ended in less learning progress than both the explicit training and the combined training. This finding suggests that at least some explicit preparation is necessary before implicit training becomes effective. Implicit training without explicit preparation resulted in less letter knowledge, a higher incidence of errors when engaging in the game, and a lower reading rate within the trained orthography. Again, the lower reading rate was also found independent of letter knowledge.

From a qualitative perspective, and focusing exclusively on explicit versus implicit techniques, we can conclude from our findings that there are no differences in educational needs between dyslexic readers and normal readers. The relative failure of isolated implicit training applies to both groups. Nevertheless, the finding that both groups can benefit from a combined instructional approach is particularly valuable for dyslexic readers because they are in strong need of print exposure. Not only do they need to make up for the considerable deficits in reading practice they have accumulated over time ([Torgesen, 2005](#)), but experimental studies also confirm that dyslexics need much more exposure to learn words by sight (e.g., [Thaler, Ebner, Wimmer, & Landerl, 2004](#)). Adding implicit training to explicit instruction is an efficient way of optimizing exposure, taking into account the limits of cognitive load.

These results are interesting in relation to the current focus on implicit techniques that capitalize on computer game environments within dyslexia intervention ([Aravena & Tijms, 2009](#); [Lyytinen, 2008](#); [Saine et al., 2011](#)). These so-called “edugames” were brought into action in the quest for new fluency-oriented intervention. Because they offer the possibility to establish massive exposure within a highly motivational environment and without high demands for cognitive load, they might be particularly suitable for dyslexia intervention. The findings of the current study indicated, however, that a combination of explicit instruction and implicit techniques provides a more powerful tool in the initial teaching of letter–sound correspondences than implicit training alone.

The results concerning the acquisition of rule knowledge in relation to the instructional approach are crystal clear. None of the children engaging solely in the edugame was able to deduce the orthographical rule by himself or herself. Evidently, to be able to apply an algorithmic spelling rule in reading, at least some portion of explicit instruction is needed, or much more time is needed, for implicit learning to come about. This finding is in line with previous results indicating that implicit learning of spelling rules may depend largely on sensitivity to the frequency with which certain combinations of

letters occur (e.g., Kemp & Bryant, 2003). Distributional features of the input can be detected only if there is a sufficient amount of exposure. It seems that, in general, children need a great deal of time to master spelling rules at school (Hilte & Reitsma, 2011; Kemp & Bryant, 2003). Thus, studying spelling rule acquisition at the lab, as in the current study, may require much more time or the use of a simpler rule structure.

Limitations, prospects, and practical implications

We adopted an artificial orthography paradigm, assuming that by this means we were able to rule out differences in previous exposure to experimental stimuli. A limitation of the current study is that the children still needed to transcribe phonemes from their native language. Therefore, we cannot rule out the possibility that dyslexic readers were put at a disadvantage at the start of the session due to a less well-specified phonemic framework; consequently, we cannot establish a cause–effect relationship between disrupted letter–speech sound binding and a deficit in phonological processing. For future research, it would be of interest to focus on further positioning this binding deficit within the etiological framework of dyslexia. The current view is that disrupted letter–speech sound binding results from a phonological deficit, but because this assumption has not been confirmed experimentally, room for alternate views remains. In fact, in two studies the development of letter–speech sound associations was found to be independent of prior phonological or orthographical knowledge (Blomert & Willems, 2010; Castles, Coltheart, Wilson, Valpied, & Wedgwood, 2009). It has even been proposed that a letter–speech sound binding deficit in itself might be the proximal cause of dyslexia (Blau et al., 2009, 2010; Blomert, 2011; Wallace, 2009). Thus, future research should further explore how letter–speech sound mapping relates to other phonological skills and whether a letter–speech sound binding deficit as a predictor of reading problems also occurs independent of a phonological deficit. An appealing avenue would then be to measure letter–speech sound binding abilities within a group of preliterate children, including children carrying a familial risk for dyslexia, and to test whether these abilities make a unique contribution in predicting future reading and spelling skills compared with typical phonological and orthographical predictors. Another way to further explore the nature of a letter–speech sound binding deficit and its relation to phonological skills is to assess letter–speech sound binding in children with reading disabilities who do not show any phonological deficit. If these children do less well than normal readers, that would indicate that this binding deficit can also manifest itself in the absence of a phonological deficit.

In addition to the relation between letter–speech sound binding and typical phonological skills, it would also be of interest to focus on possible correlations with other cognitive abilities, especially those that have been linked to dyslexia in previous studies such as sensitivity to statistical regularities (Pavlidou, Kelly, & Williams, 2010) and visual attention (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012). There might be more cognitive deficits that are associated with hampered letter–speech sound binding.

Another limitation of our study is that learning letter–speech sound correspondences for a second time within the same language may involve different learning mechanisms than letter–speech sound learning the first time. Interestingly, imaging studies within the artificial orthography paradigm indicated that brain changes occurring during the learning of a novel script seemingly parallel the changes that took place during the first encounter with an already familiar script (Hashimoto & Sakai, 2004; Maurer et al., 2010). Nevertheless, we need to be cautious in generalizing the current findings to the natural process of learning letter–speech sound correspondences for the first time.

Finally, our findings may have implications for assessment. The fact that differences in letter–speech sound learning can be detected during an initial phase provides opportunities for designing more process-oriented diagnostic tools. Currently, there is a paucity in our knowledge of factors that predict responsiveness to dyslexia intervention (Frijters et al., 2011; Hoeft et al., 2011; Tijms, 2011). Process-oriented diagnostic tools that focus on learning are potentially capable of predicting future reading gains in dyslexia intervention. In future research, it would be interesting to reshape the training used in the current study into a practical diagnostic tool. Accordingly, one could examine from which age onward differences in letter–speech sound learning can be detected by this tool. Because

it can be applied independent of phonological or reading instruction, it might be adequate for pre-schoolers as well, providing opportunities for early detection of dyslexia.

In summary, our results contribute to the understanding of the etiology of dyslexia. We found convincing behavioral evidence for disrupted letter–speech sound learning in dyslexia. With the use of an innovative experimental design with an artificial orthography, we were able to see letter–speech sound learning in action at our lab. Our results indicated that learning difficulties within this domain can be manifested at any time and that they cannot be attributed to differences in prior exposure to the concerned correspondences. Importantly, we also found evidence that disrupted letter–speech sound binding immediately affects reading performance irrespective of letter knowledge. Moreover, in support of the external validity of our study, the results indicated that reading proficiency in Dutch was correlated with reading proficiency in the artificial script. Together with other recent findings regarding letter–speech sound learning in dyslexia, our results invite a more prominent role for letter–speech sound learning within the etiological framework of dyslexia. We hope that our innovative design will inspire new research applying the artificial orthography paradigm to further elucidate the nature of letter–speech sound binding and its relation to phonological processing and reading development.

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