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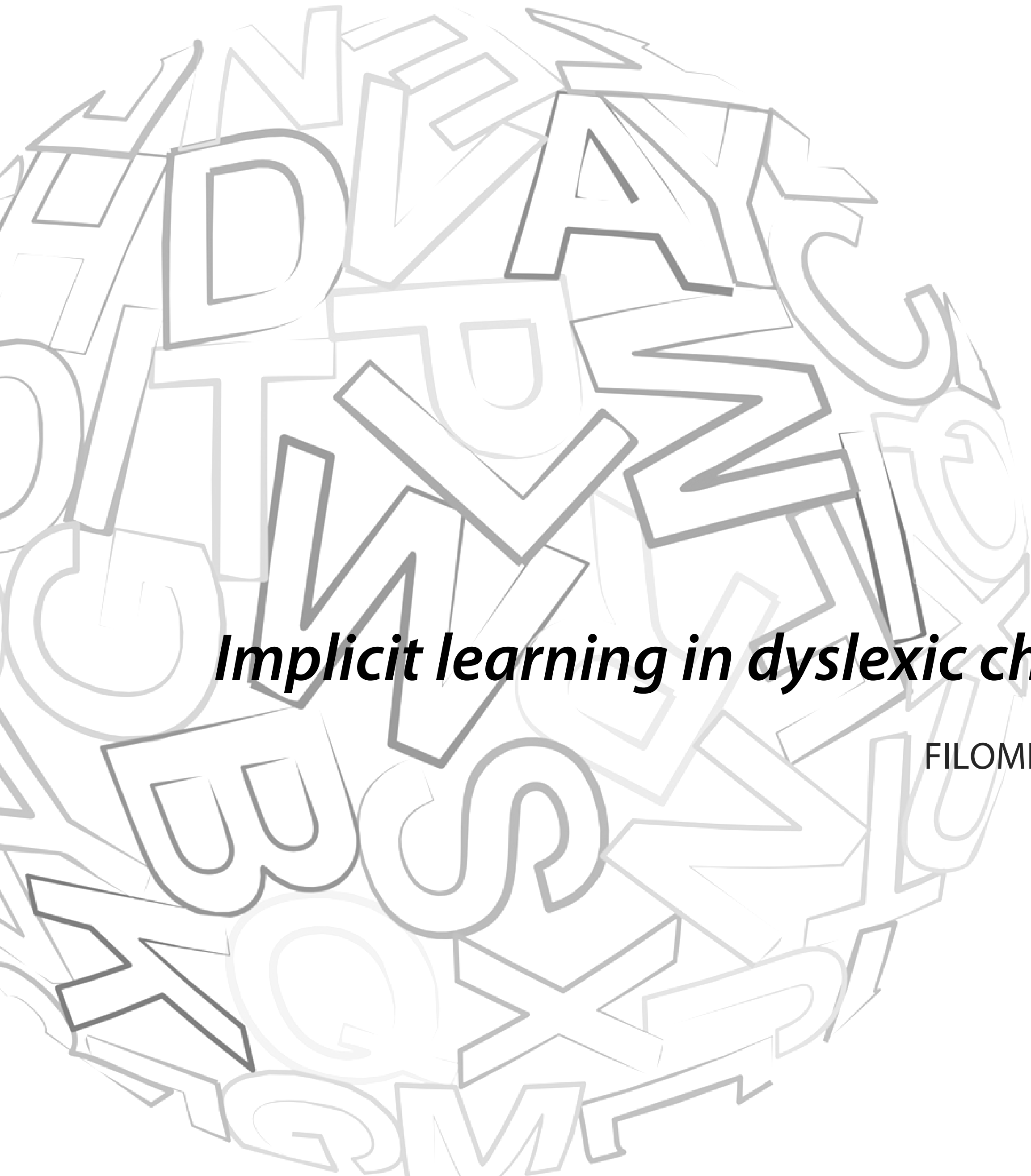

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MESTRADO EM NEUROCIÊNCIAS COGNITIVAS E NEUROPSICOLOGIA

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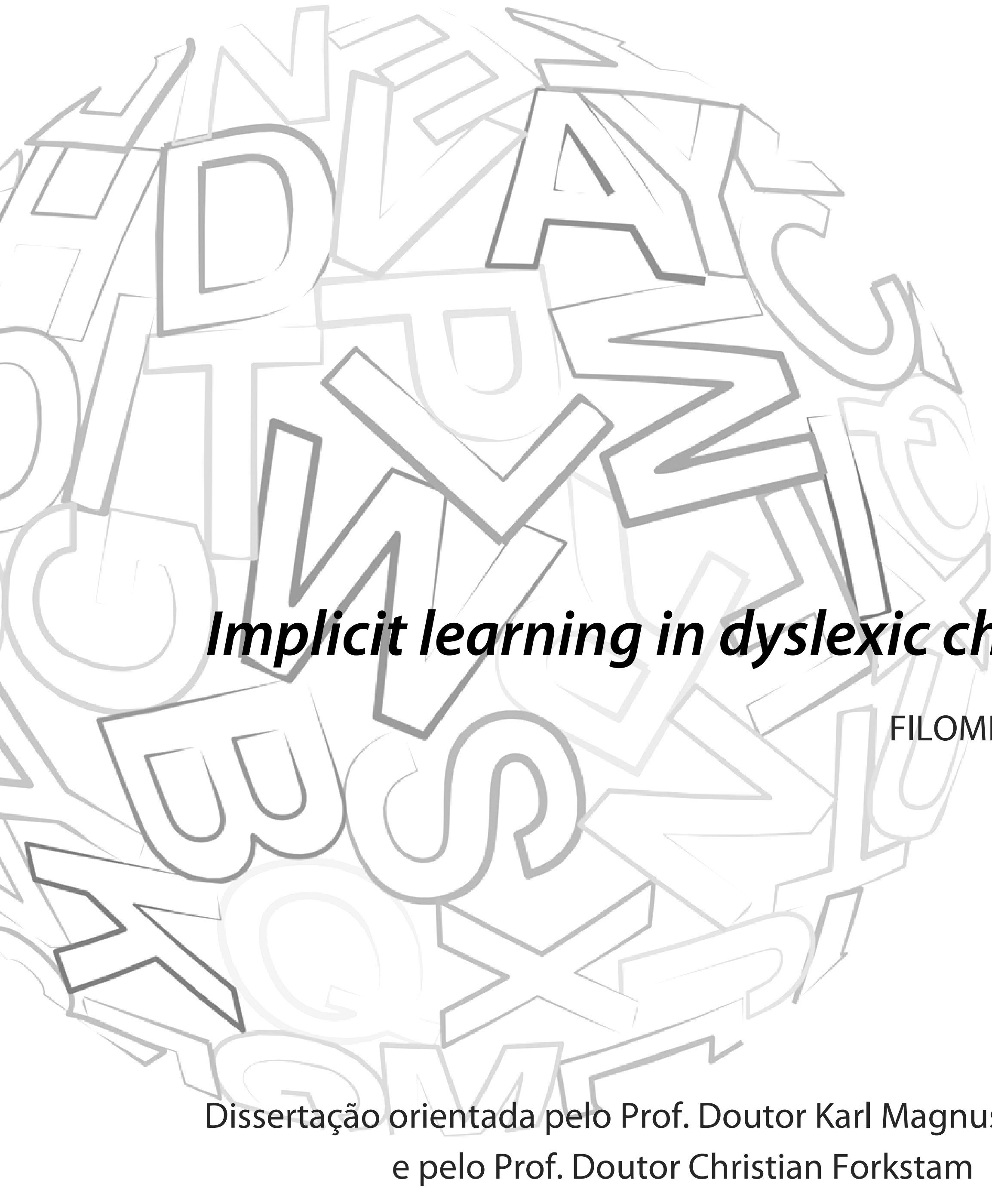

Implicit learning in dyslexic children

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TABLE OF CONTENTS

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RESUMO

A dislexia é uma perturbação específica de aprendizagem de origem neurobiológica, caracterizada por dificuldades no reconhecimento exacto e/ou fluente de palavras escritas e por dificuldades ortográficas e de descodificação. Estas dificuldades coexistem com capacidades cognitivas normais e surgem apesar de existir instrução e condições sócio-económicas adequadas. Ao longo das últimas décadas tem-se observado uma explosão de estudos dedicados a identificar quais os défices manifestados pelos disléxicos e qual a sua causa. Mais recentemente, alguma desta investigação tem-se centrado nas capacidades de aprendizagem implícita e eventuais défices nestas capacidades apresentados pelos disléxicos.

A aprendizagem implícita é definida pela aprendizagem não intencional de informação complexa, desenvolvida de um modo automático apenas pela constante exposição às regularidades ambientais. Esta aprendizagem ocorre sem que a pessoa tenha intenção de o fazer e sem conhecimento explícito e verbalizável do conteúdo aprendido. Na aprendizagem da leitura e escrita as crianças estão expostas não só a processos explícitos, mas também a processos implícitos. Inicialmente, as crianças adquirem explicitamente as correspondências grafema-fonema e posteriormente estas correspondências passam a ser aplicadas, e até adquiridas, de um modo implícito (Gombert, 2003; Sperling, Lu, & Manis, 2004). Simultaneamente, as regularidades dos sistemas de escrita podem também ser extraídas implicitamente, sob a forma de padrões visuais (ortografia), palavras ditas oralmente e associadas a esses padrões (fonologia e léxico) ou pelo significado que estes padrões activam (morfologia e léxico) (Gombert, 2003). Processos implícitos estarão também presentes quando a aquisição de significado associado a este padrão ortográfico é efectuado através do contexto (Howard, Howard, Japikse, & Eden, 2006). Esta combinação de processos explícitos e implícitos na aquisição da leitura leva-nos a pressupor que um défice nas capacidades de aprendizagem implícita pode contribuir para as dificuldades apresentadas pelas crianças disléxicas. Contudo, os poucos estudos sobre a aprendizagem implícita em disléxicos têm revelado resultados díspares. Enquanto alguns autores referem que os disléxicos apresentam um défice na aprendizagem implícita (Pavlidou & Williams, 2010; Pavlidou, Williams, & Kelly, 2009; Sperling et al., 2004; Stoodley, Harrison, & Stein, 2006; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), outros estudos

apontam para que estas capacidades estejam intactas em crianças e adultos disléxicos (Kelly, Griffiths, & Frith, 2002; Roodenrys & Dunn, 2008; Russeler, Gerth, & Munte, 2006; Waber et al., 2003). Alguns autores referem que esta discrepância de resultados se deve à utilização de diferentes provas, que podem estar a avaliar diferentes processos de aprendizagem implícita e que os disléxicos podem ter défices apenas em alguns destes processos (Howard et al., 2006).

Com o presente estudo pretendemos clarificar esta questão, investigando se crianças disléxicas apresentam capacidades de aprendizagem implícita. Para tal, foi utilizado um paradigma de aprendizagem implícita complexo, a aprendizagem de gramática artificial, mas adaptado a crianças disléxicas. Adicionalmente, examinámos a relação entre a aprendizagem implícita e as competências de leitura e outras capacidades relacionadas com a leitura.

Participaram no estudo doze crianças com diagnóstico ou suspeita de dislexia, do 2º ao 4º ano de escolaridade. Este grupo foi emparelhado com dois grupos de controlo: um grupo equivalente em termos de idade e escolaridade e outro grupo equiparado em termos de capacidade de leitura, todos do 1º ano de escolaridade. Todos os grupos realizaram provas complementares de leitura, escrita, consciência fonológica, nomeação rápida, vocabulário e memória de trabalho.

A experiência de aprendizagem de gramática artificial foi dividida em três sessões, realizadas em três dias seguidos. No início de cada sessão os participantes realizavam uma prova de memória (as crianças memorizavam sequências de símbolos coloridos e posteriormente tinham de reproduzir a sequência memorizada, com recurso a uma caixa de resposta apropriada), na qual eram expostos a sequências gramaticais, sem terem conhecimento desse facto. Na última sessão os participantes foram informados de que as sequências que tinham visto na prova de memória obedeciam a conjunto de regras complexo e foi-lhes pedido que classificassem um novo conjunto de sequências, constituído por sequencias gramaticais e não gramaticais. No fim de cada sessão, os participantes eram entrevistados no sentido de se verificar se estes possuiam conhecimento explícito acerca das regras subjacentes às sequências gramaticais.

Os resultados revelaram que não havia diferenças significativas no desempenho dos disléxicos e dos dois grupos de controlo na prova de classificação de sequências.

Este resultado indica que todas as crianças deste estudo extraíram as regularidades dos estímulos ao mesmo nível. Foi ainda calculado um índice de discriminação (d') que também não diferiu entre os grupos. Apesar de não haver diferenças entre grupos, o desempenho geral dos participantes foi mais baixo do que o esperado. Procedeu-se então a uma análise individual do desempenho dos sujeitos e verificou-se que alguns disléxicos apresentavam índices de discriminação bastante elevados. O mesmo padrão foi observado nos grupos de controlo. Através das entrevistas pós-experimentais verificámos também que os sujeitos não tinham conhecimento explícito acerca das regras subjacentes às sequencias gramaticais. Todos estes dados levam-nos a concluir que os disléxicos são capazes de extrair as regularidades implícitas de uma gramática artificial ao mesmo nível que as crianças sem défices de leitura.

Os nossos dados levam-nos a supor que os diferentes resultados observados nos estudos de aprendizagem implícita em disléxicos pode dever-se não só à grande variação das provas utilizadas para avaliar a aprendizagem implícita (diferentes paradigmas, com diferentes estímlos, diferentes comprimentos de sequências, diferentes tipos de resposta e consequentemente com procedimentos experimental diferente), mas também devido às características da amostra. Os critérios de inclusão dos disléxicos nos estudos também diferem de um estudo para outro e muitas vezes não há qualquer reavaliação das capacidades dos disléxicos. Simultaneamente as diferenças individuais dentro do grupo dos disléxicos são também habitualmente ignoradas. Estas diferenças individuais podem estar na origem desta discrepância de desempenho apresentado pelos disléxicos nos diferentes estudos. Estudos futuros, com maiores amostras de disléxicos e com uma avaliação mais detalhada das suas características individuais podem clarificar esta questão.

Em suma, o nosso estudo revela que a capacidade de aprendizagem implícita de gramática artificial está presente em crianças disléxicas. O ensino da leitura e os programas de intervenção na dislexia podem explorar estas capacidades de aprendizagem implícita preservadas nos disléxicos para auxiliar os processos explícitos na aquisição das competências de leitura.

Palavras-chave: dislexia; aprendizagem implícita; aprendizagem de gramática artificial; aquisição da leitura; desenvolvimento

ABSTRACT

Children with dyslexia have consistently presented a variety of deficits that prevent them from achieving full reading proficiency. Previous research has reported conflicting results concerning the implicit learning abilities of dyslexic readers. The present study investigated the implicit learning abilities of dyslexic children using an artificial grammar learning task. Twelve children with developmental dyslexia and two control groups – one matched for age and other for reading skills – participated in the study. After three acquisition days where participants were exposed to symbols sequences with an underlying grammatical structure, subjects were tested in a grammaticality classification task. Results revealed similar performance in all groups and suggest that the implicit learning abilities are unimpaired in dyslexic children.

Keywords: dyslexia; implicit learning; artificial grammar learning; reading acquisition; child development

INTRODUCTION

Literacy is crucial for social and human development in a modern society. Reading requires the transformation of culture-specific symbols into units of sound in order to gain access to meaning. Reading is a complex process that requires adequate language comprehension and fluent word identification.

The discussion about reading and writing models is prolific in literature, although no proposed model is definitive and the debate is still ongoing (for an overview see Ehri, 2007; Rack, Hulme, & Snowling, 1993; Siegel, 1993). Reading theories assume that for the development of fluent reading there has to be a shift from slow phonological decoding to automatic recognition of whole word-forms. This automated performance implies that complete words or morphemes are linked directly to their phonological or semantic counterpart. Most of these theories suggest that reading development unfolds in a succession of distinctive phases in which skills emerge, change and develop. Even though there are different nuances among the reading development theories, we can extract some topics on which there is common agreement. In a pre-reading phase, children adopt a visual cue approach in which visual and contextual associations are made. This phase is labelled by some authors as logographic or pre-alphabetic (Ehri, 2007; Stuart & Coltheart, 1988). Typically the child begins to learn letters and to establish associations between them and speech sounds with formal schooling. By the end of this alphabetic phase, children will explicitly know and use correspondence rules between individual graphemes and phonemes (see Ehri, 2007 for a detailed explanation and also how this phase is subdivided by some authors). Finally, in a consolidation phase, children are able to read based on the direct matching of familiar written words with the internally represented abstract letter groups built during the alphabetic phase. This leads to the development of reading automaticity, as the reader recognizes the pronunciations and meanings of written words immediately upon seeing them (Ehri, 2007; Frith, 1986).

Siegel (1993) emphasizes that the development of reading skills depend on five important processes, such as phonological processing (the understanding of grapheme-phoneme conversion rules and the exceptions to these rules), syntactic awareness (the ability to understand the syntax of the language), working memory (the reader must decode and/or recognize words while remembering what has been read and retrieving information such as grapheme-phoneme conversion rules), semantic processing (the understanding of meaning) and orthographic processing (the understanding of writing conventions and correct spellings of words).

Poor readers present difficulties when decoding new words, they take longer to learn visually presented words, they read familiar words slowly and take longer to unitize them (Ehri, 2007). In this sense, poor readers may present characteristics of an inexperienced reader beginner and may never attain a necessary level of reading fluency and automaticity.

Dyslexia

The definition of dyslexia is intensely discussed and the nature of this condition is still debated. Typically, dyslexia is defined as a mismatch between reading achievement and general intellectual capacity, that is, an unexpected reading difficulty in children and adults who otherwise possess average intelligence and motivation necessary for accurate and fluent reading. This underachievement is the central feature of dyslexia. It occurs in the absence of other cognitive disabilities and are not due to extraneous factors such as sensory acuity deficits, socio-economic disadvantage or lack of exposure to high quality literacy instruction (Lyon, Shaywitz, & Shaywitz, 2003; Tunmer & Greaney, 2010; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Dyslexia is probably the most common learning disorder in children and affects approximately 5.4% of the Portuguese students from second to fourth grade (Vale, Sucena, Viana, & Correia, 2010). In a recent survey (Ise et al., 2011), Portuguese teachers found that 21% of the students in the third grade were poor readers (with or without spelling problems). These students are considered to be at risk for failure in academic and social life unless effective support systems can modify such an outcome (Ise et al., 2011).

A vast number of studies have identified the most common deficits in dyslexia as impairment in *phonetic perception* (encoding phonological information), *phonological awareness* (access and manipulation of phonological information), *lexical retrieval* (retrieving phonological information from semantic memory), *verbal working memory* (retaining phonological information in short-term memory), *phonological recoding* (translating letters and letter patterns into phonological forms), and *reading comprehension* (Siegel, 1993; Tunmer & Greaney, 2010; Vellutino et al., 2004). These deficits typically persist throughout adulthood, even though the individual might develop compensating strategies (Shaywitz & Shaywitz, 2005; Vellutino et al., 2004).

Several theories and explanations have been presented in an attempt to clarify dyslexia. These theories are best categorized at either a biological or a cognitive level (for a review see Frith, 1999; Vellutino et al., 2004) and they try to explain the behavioural or clinical signs manifested in dyslexia.

Genetic studies do not indicate that specific genes cause dyslexia, but a susceptibility to reading difficulties (Gilger, 2002). Despite the prominent role of environmental factors commonly referred in this studies, chromosomes 6 and 15 has been associated with reading disability in studies of familial dyslexia and in mono- and dizygotic twins (Grigorenko, 2001; Smith, Pennington, Kimberling, & Ing, 1990).

Anatomically, the wide panoply of brain studies in dyslexic show very inconsistent results, indicating that the underlying neuroanatomical basis of dyslexia is complex and not reducible to a single finding or brain region. In *post mortem* studies of dyslexics, a greater symmetry between brain hemispheres has been observed (Humphreys, Kaufmann, & Galaburda, 1990). Several studies using anatomical magnetic resonance imaging (MRI) typically indicate differences between dyslexics and controls in the planum temporale and other structures in the left hemisphere (see Vellutino et al., 2004 for a brief review). However, these studies are often of small samples or differ in the imaging methods used. More precise anatomical MRI studies, which have controlled age, gender, and handedness show a small reduction in the size of the left temporal lobes (Schultz et al., 1994) and reductions in the size of the insula and anterior superior neocortex in both hemispheres (Pennington et al., 1999) in the dyslexic groups.

It has been suggested that some dyslexics present structural and functional anomalies in the magnocellular system - tracts of large neurons that have a high degree of sensitivity to movement and rapid changes in the visual field. According to the proponents of the magnocellular deficit hypothesis (Stein & Walsh, 1997), dyslexic readers suffer from magnocellular impairment possibly caused by a disorganized magnocellular layer and smaller magnocells in the lateral geniculate nucleus (LGN - a relay station of the visual projection pathways from the eye to the visual cortex, see Livingstone & Hubel, 1988). In fact, Livingstone and colleagues (1991) provided evidence from a post mortem dissection showing that magnocells in the LGN of dyslexic readers were 30% smaller and more disorganized than those of controls. These abnormalities seem to affect the visual system, which might explain the visual perceptual and/or oculomotor deficits presented by dyslexics and might account for part of the difficulties in discriminating and processing orthographic information (Stein & Walsh, 1997).

A failure in the magnocellular system can affect eye movement control and this dysfunction might have two implications for dyslexic readers. First, taking into account the perceptual consequences like moving and merging letters, it is proposed that dyslexic readers suffer from a visual perceptual deficit that hinders them from accurately perceiving a letter sequence they read. Secondly, divergent eye movement patterns during reading can make it more difficult to perceive an unknown letter sequence and therefore to more and longer fixations during reading (Stein & Walsh, 1997). Although the magnocellular theory might appears appealing, some authors suggested that a possible dysfunction of the magnocellular pathway is not related to the cognitive level and even if dyslexic readers do have reduced magnocellular sensitivity, this deficit does not necessarily have consequences for visual perception and oculomotor control during reading (Frith & Frith, 1996).

Nicolson and Fawcett (1999) proposed the cerebellar deficit hypothesis as an alternative or parallel mechanism to the magnocellular defect in dyslexics. They noticed that a high proportion of dyslexic children show behavioural evidence of abnormal cerebellar function (Fawcett & Nicolson, 1999). In addition, they observed direct neurobiological evidence of cerebellar impairment in dyslexic adults (Nicolson et al., 1999). Since the cerebellum plays a role in motor control and speech articulation, abnormalities of the cerebellum would lead to dysfunctional articulation, which in turn might lead to a deficient phonological representation. The cerebellum also plays a role in the automatization of tasks, such as reading. A weak capacity to automatize would affect, among other things, the learning of grapheme-phoneme correspondences (Nicolson & Fawcett, 1999; Nicolson, Fawcett, & Dean, 2001a). Nicolson and colleagues (2001a) speculated that an abnormal cerebellar function triggers a developmental schema of problems causing reading, writing and spelling difficulties.

Although the evidence suggests a neurobiological basis of dyslexia, several cognitive theories has been presented to try to explain dyslexia, of which the phonological deficit theory seems to have the widest consensus among investigators (Shaywitz & Shaywitz, 2005; Vellutino et al., 2004). The phonological theory postulates that dyslexics have a specific impairment in the representation, storage and/or retrieval of speech sounds (Ramus et al., 2003). There is convergent evidence that phonological coding deficits are an underlying cause of reading difficulties. These deficiencies in phonological skills are commonly expressed by dyslexics in a variety of phonological tasks, including tasks requiring verbal short-term memory (e.g. digit span), phonological awareness (e.g., phoneme deletion and rhyme judgments), phonological decoding (e.g., pseudoword reading), and lexical retrieval (e.g., rapid automatized naming) (Hulme, Snowling, Caravolas, & Carroll, 2005; McDougall, Hulme, Ellis, & Monk, 1994; Ramus et al., 2003; Ramus & Szenkovits, 2008; Swan & Goswami, 1997a, 1997b).

Some authors suggest that the phonological deficit hypothesis is an insufficient explanation for the observed reading disabilities and propose that dyslexics present a visual deficit. According to Bowers and Wolf (1993) these naming deficits are caused by a disruption in the integration of the phonological and visual counterparts of printed words, which, in turn, will impair the child's ability to detect and represent orthographic patterns – the orthographic redundancies and regularities will not be processed with sufficient speed, suggesting a disruption in automatic reading processes. In this sense, phonological and naming deficits seem to be differentially related to reading skills – phonological awareness is correlated with accuracy in word identification and letter-sound decoding and rapid naming is associated with speed of word identification and letter-sound decoding (Manis, Doi, & Bhadha, 2000; Vellutino et al., 2004). Wolf and Bowers (1999) further propose that the reading disabilities can be divided in three subtypes of impairment: some dyslexics present deficits in their phonological abilities; in others, we observe naming deficits, and a third subtype present a combination of both deficits – the double deficit theory. However, despite some recent studies support this theory (Araújo, Pacheco, Faísca, Petersson, & Reis, 2010), there is still controversy around it (Vellutino et al., 2004) and other explanations for deficits that dyslexics present arise.

Defining dyslexia is a difficult task. As previously suggested by Frith (1999) this concept is clearer if we consider the biological, cognitive and behavioural effects linked together with the impact of the environmental factors. The consensus seems to be that dyslexia is a neuro-developmental disorder with a biological origin, which affects written language and with a range of clinical manifestations. One of the behavioural manifestations of dyslexia that have raised interest among investigators in the past decade is the implicit learning deficit. It has been proposed that dyslexics could have an implicit learning deficit that prevents them to achieve proficient reading skills (Folia et al., 2008; Gombert, 2003; Howard et al., 2006; Sperling et al., 2004). This is the focus of our present study and therefore we will briefly explain implicit learning in this context and how it can affect reading acquisition.

Implicit learning

Implicit learning is a non-declarative learning of complex information in an incidental manner, without awareness of what has been learned (Reber, 1967; Seger, 1994). This type of learning occurs in an automatic and unintentional fashion, developed simply by constant exposure to environmental regularities, without explicit verbalizable knowledge of what was acquired, in contrast to explicit learning (Kaufman et al., 2010). Moreover, the result of implicit learning is implicit knowledge in the form of abstract representations (Forkstam & Petersson, 2005; Reber, 1967). In Seger's (1994) implicit learning review, four characteristics are described as fundamental for the the phenomenon of implicit learning be present:

1. Limited explicit accessibility to the acquired knowledge (i.e. subjects typically cannot provide sufficient or, in many cases, any explicit account of what they have learned);
2. The nature of the knowledge acquired is more complex than simple associations or based on simple exemplar-specific frequency counts;
3. Implicit learning does not involve explicit hypothesis testing but is an incidental (automatic) consequence of the type and amount of processing performed on the stimuli;

4. Implicit learning depends on mechanisms other than those used in inducing explicit knowledge. This can be observed in the amnesic patients, were implicit learning is preserved.

Additionally, it has been suggested that implicit learning is an evolutionary early process, independent of age and developmental level, presents a lower population variance, i.e., the implicit functions show little individual-to-individual variation and even IQ independence, and robustness over time, that is, after months or even years, or even after brain lesion, subjects still retain implicit learning tasks (Allen & Reber, 1980; Fendrich, Healy, & Bourne, 1991; Reber, 1992).

Implicit learning certainly involves activity in multiple brain regions. In general, studies suggest that distinct networks might be involved depending on whether subjects are aware or not of the material they learn and seem to support that learning directly produces changes in the brain regions involved in performance; and that additional regions are involved when subjects report awareness (Cleeremans, Destrebecqz, & Boyer, 1998).

In the literature, the most referred brain regions related with implicit learning are the basal ganglia, the association cortex and the frontal cortex. The basal ganglia appears to be involved in aspects of response programming, the association regions appear to be involved in perceptual aspects of implicit learning, and the frontal lobes appear to be involved in the evaluation of implicit knowledge in making fluency judgments (Forkstam, Hagoort, Fernandez, Ingvar, & Petersson, 2006; Forkstam & Petersson, 2005; Seger, 1994). Moreover, some studies have suggested that the medial temporal lobe memory system, including the hipoccampus, may be involved in implicit learning (Schendan, Searl, Melrose, & Stern, 2003). However, the role of the medial temporal lobe memory system remains unclear, since amnesic patients with medial temporal lobe lesions show that this region has a limited role in several implicit learning tasks (Gagnon, Foster, Turcotte, & Jongenelis, 2004).

Implicit learning is usually studied with paradigms that vary the stimulus structure and the response modality. The most common stimulus types are visual patterns, sequences and functions. Tasks also vary in the different response modalities: conceptual fluency (subjects make ratings or classify items, usually reporting that they rely on their intuition or feelings to make such judgments), efficiency (subjects show that they have induced knowledge by their increased speed or accuracy in processing the information), or prediction and control (subjects demonstrate learning by accurately predicting or controlling some aspect of the stimuli (Forkstam & Petersson, 2005; Seger, 1994). Nine different learning paradigms result as a combination of these two properties (stimuli structure and response modality), but the most intensely investigated are the serial reaction time task and the artificial grammar learning. The serial reaction time task (SRTT - Nissen & Bullemer, 1987) is a visual-motor procedural learning task, i.e., has a motor component, whereas the artificial grammar learning task (AGL - Reber, 1967) is a more highly complex implicit learning paradigm that relies on cognitive processes. The SRTT is a simple task in which, usually, the subject has to press a button that corresponds to a stimulus light (see Figure 1). The light appears in a set sequence of typically 10 positions. Implicit learning is inferred from faster reaction times in responding to reoccurring versus, for example, random sequences, while the participants typically report no or little awareness of reoccurring sequences.

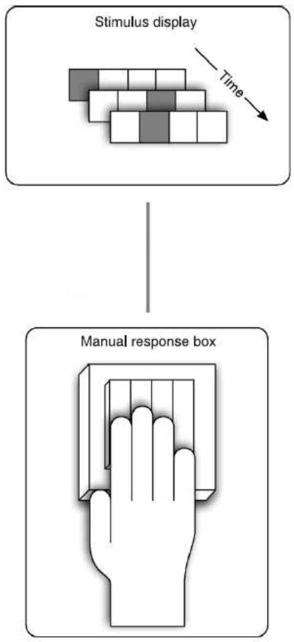

FIGURE 1. The serial reaction time task – the subject has to press a button that corresponds to a stimulus light (adapted from Clark & Ivry, 2010).

In studies of artificial grammar learning (see Figure 2), subjects typically process a sample of grammatical sequences during the acquisition phase (usually they are asked to memorize or merely observe the acquisition sequences). Subjects become better at memorizing sequences as this acquisition phase progresses, which suggests that the sequences regularities may be facilitating learning (Reber, 1967). Afterward, subjects are informed that the sequences were generated by a complex set of rules and new sequences are classified as grammatical or non-grammatical on the basis of the immediate intuition ('guessing'). Participants typically perform reliably above chance with little or none explicit knowledge about the rules followed by the stimuli. Subjects can also be instructed to classify the new sequences with a preference judgment (like/dislike). In this case, no reference to the underlying grammar is needed and the subjects are therefore completely uninformed about an underlying structure in the acquisition material. This classification variant is sensitive to the same knowledge as grammaticality judgments and related to these judgments (Forkstam, Elwér, Ingvar, & Petersson, 2008).

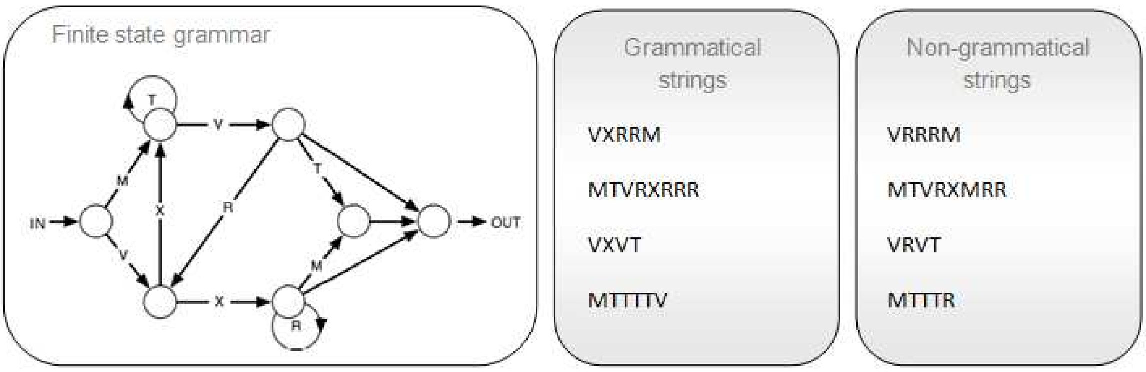

FIGURE 2. An example of finite state grammar (adapted from Reber & Allen, 1978). Grammatical strings are generated by entering the grammar through the 'in' node and by moving from node to node until the 'out' node is reached. Non-grammatical strings are produced by switching at least one letter to another one. The sequences can be presented as strings of letters, symbols, color patches and tones amongst others.

In artificial grammar learning, one of the main topics of discussion concerns what is acquired by the participants, and how they learn it. Studies suggest that participants implicitly acquire rule-based knowledge as well as exemplar-specific knowledge. According to the first view, participants are learning abstract rules that govern formation of letter sequences for later use during the grammar classification task (Reber, 1967). On the other hand, participants are gaining knowledge specific to the training exemplars, and this exemplar-specific learning is used to make their judgments. Participants also demonstrate sensitivity to chunk strength, the number of times the bi-gram or tri-gram chunks within the item have been repeated across the training set. For each letter sequence, the overall chunk strength can be calculated by averaging the chunk strength of the bi-grams and tri-grams. There has been experimental support for both rule-based and exemplar-based learning in the AGL task. Depending on the specific constraints of the tasks, different mechanisms might underlie the performance in an artificial grammar learning task: knowledge based on n-grams or knowledge based on abstracting grammatical structure (Meulemans & Van der Linden, 1997).

Implicit learning may play an important role in procedural knowledge complex real-world systems comprehension, structuring our skills, perceptions, and behaviour (Kaufman et al., 2010). One of these skills is reading. Some authors (Folia et al., 2008; Gombert, 2003; Sperling et al., 2004) argue that reading involves a blend of explicit and implicit learning abilities, so any deficits in any of these abilities could prevent learners from becoming fluent readers.

Implicit learning and dyslexia

When a child begins to learn to read through formal instruction, he/she is exposed to not only explicit processes, but also to implicit processes. The writing systems (as language itself) exhibit many regularities that can be extracted and predicted without explicit teaching (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Gombert, 2003). According to Gombert (2003) these regularities may take the form of visual patterns (orthography), spoken words associated with these patterns (phonology and lexicon) or the meaning activated by these patterns (morphology and lexicon). Furthermore, learning to read involves, initially, an explicit acquisition of the grapheme-phoneme correspondence and afterwards these correspondences are applied and even acquired implicitly (Gombert, 2003; Sperling et al., 2004). Howard and colleagues (2006) also suggest that the orthography-meaning correspondence is learned explicitly through picture-word matching and then implicitly through context. This blend of explicit and implicit processes in reading acquisition lead us to assume that a deficit in implicit learning might contribute for the difficulties presented by dyslexic children. However, the growing literature on implicit learning and dyslexia is so far inconclusive and no clear demonstration of a direct link between implicit learning abilities and reading and writing competences (see Folia et al., 2008 for a brief review).

Several plausible mechanisms as been suggested by which a selective weakness in implicit learning could account for the phonological processing and reading problems that feature in dyslexia: automaticity, phonemic awareness and orthographic awareness (Howard et al., 2006). The cerebellar impairment hypothesis (Nicolson & Fawcett, 1999; Nicolson, Fawcett, & Dean, 2001b) suggests that children with dyslexia have unusual difficulty in automatizing any skill, whether motor or cognitive (including reading, spelling and phonological skill). Although theoretically the authors find a link between the automaticity deficits and the reading skill deficits presented in dyslexics, the evidence is still indirect and further studies may shed a light on this association. On the other hand, Howard and colleagues, (2006) argue that the implicit sequence learning deficits are consistent with hypothesis that poor implicit learning could prevent the establishment of good phonological processing as well as learning orthographic-phonological representations. These authors found a significant correlation between reading and implicit sequence learning and suggest that a combination of a phonological deficit with an impaired sequence learning system could manifest as a failure in applying implicit or probabilistic rules required for fluent application of grapheme-phoneme correspondences and therefore leading to reading disability (Howard et al., 2006).

Other studies claim that dyslexics present impairment in implicit learning abilities. Vicari, Marotta, Menghini and Petrosini (2003) presented two types of tasks to dyslexic children and age matched controls: an implicit and an explicit simple reaction time task (SRTT) using colours sequences. While in the explicit task dyslexics performed at the same level as controls did, on the implicit task dyslexics showed reduced learning. Adult dyslexics also show impairment in a similar implicit SRTT with number sequences as stimuli (Stoodley et al., 2006). Both (Stoodley et al., 2006; Vicari et al., 2003) suggest that their findings may indicate that dyslexics present a deficit in the automatization function of the cerebellum. These behavioral findings were further replicated in an fMRI study of adult dyslexics (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006).

Sperling, Lu and Manis (2004) compared the performance on implicit and explicit tasks, selecting adult poor readers as participants. These authors observed not only that poor readers took longer to learn the implicit rule and with lower overall accuracy, but also that the task performance was related to three different word reading and phonological decoding tasks. Therefore, the investigators (Sperling et al., 2004), similarly to Vicari and colleagues (Menghini et al., 2006; Vicari et al., 2003) and Stoodley and collaborators (2006), concluded that implicit learning is related to reading ability and that it is deficient in adult poor readers, while explicit learning is normal.

While these studies point to deficits in implicit learning abilities, others show that these abilities are intact. Kelly, Griffiths and Frith (2002) compared dyslexic and non-dyslexic university students on a SRT paradigm, where spatial and non-spatial sequences were presented. Both groups showed performance patterns consistent with implicit sequence learning, although dyslexics presented slower reaction times. The same pattern was found by Roodenrys and Dunn (2008). They used a simple cued reaction time task to investigate dyslexic children's implicit learning performance and their results were consistent with the Kelly and colleagues (2002) results: despite an overall slowing in response times, dyslexic children show the same degree of implicit learning as normal readers, thus, providing evidence for an unimpaired implicit learning mechanism in dyslexic individuals. In addition, Waber and collaborators (2003) were unable to document an association between reading ability and the implicit learning of motor sequences. Based on data from a very large sample of children with a range of reading competence they used regression analyses to predict performance on the serial reaction time task and found that reading ability did not reliably predict performance on the task.

So far, studies lead to the conclusion that in some cases dyslexics are impaired on implicit learning tasks, but not in others. This discrepancy in the results of implicit learning in dyslexics can be due to the utilization of different task demands that could tap into different implicit learning processes (Howard et al., 2006; Roodenrys & Dunn, 2008). To clarify this issue, Howard and colleagues (2006) tested adults with history of dyslexia with two different implicit learning tasks an alternating serial response time task and a spatial context learning task. Results revealed that dyslexics showed an impairment only in the serial response time task (and a significant positive correlation between this task and reading ability). In contrast, the opposite was revealed for the spatial context learning task. In a recent study, Jiménez-Fernández, Vaquero, Jiménez and Defior (2010) reported similar results: dyslexic children failed to learn a sequence task, but this implicit learning deficit was not extended to other forms of non-sequential, implicit learning such as contextual cueing. These findings indicate that dyslexics are only impaired in some types of implicit learning and can account for the seemingly inconsistent results presented in the different studies of implicit learning in dyslexia. On the other hand, Vicari and colleagues (2005) found that dyslexic children were impaired on two tasks, that they considered as implicit: the standard SRTT (similar to previous studies made by these authors) and the mirror drawing task. However, and as Roodenrys and Dunn (2008) point out, the mirror drawing task does not meet the usual criteria for an implicit learning task, as it is possible for explicit processes to contribute to performance in this task. Mirror drawing is usually described as tapping procedural memory and so Vicari et al.'s (2005) finding might just as well be interpreted as showing a deficit in procedural memory rather than a general deficit in implicit learning.

Russeler, Gerth and Munte (2006) also tried to elucidate this issue using the artificial grammar learning (AGL) in addition to the SRTT paradigm. The AGL task differs from the SRT task in the involvement of the motor system and is thought to be a more complex task. In contrast to some of the previous research, Russeler and colleagues (2006) found that the adult dyslexics were unimpaired on the SRT and AGL tasks.

Recently, Pavlidou and colleagues presented two studies where dyslexic children showed impaired implicit learning capacities using the AGL paradigm (Pavlidou, Kelly, & Williams, 2010; Pavlidou et al., 2009). The authors (2009) developed a grammar with geometrical shapes, specifically designed for children, and manipulated the instructions in order to create two experimental conditions: in the first experiment subjects were told to observe the stimuli (implicit condition) and in the second experiment subjects were instructed to memorize the presented stimuli (explicit condition). After the training phase, subjects were informed about the complex ruled nature of the stimuli and asked to make grammaticality judgements of a new sequence set. In both conditions, the typically developing group manage to perform above chance while the dyslexic group did not perform better than chance. Pavlidou and colleagues (2009) concluded that the implicit learning abilities are consistently diminished in dyslexics, irrespective of the nature of the instructions. In a second study, Pavlidou and colleagues (2010) criticized their previous study, arguing that the experimental designed had some limitations (not being adapted to children). They then presented a new variant of the AGL task, with less training and testing items to reduce memory load and making use of a new recall technique during the training phase, the perfect free recall (PFR - subjects are instructed to recall the training items until they do it without errors). In this study (Pavlidou et al., 2010) the performance was measured not only by the grammatical judgments of new sequences but also with the PFR score. Results revealed no differences between dyslexics and age-matched controls in the PFR scores. However, on the grammaticality test, the typically developing children were able to distinguish between grammatical and non-grammatical sequences while dyslexics responded at chance level. Pavlidou and colleagues (2010) argued that these results reflect that, even though dyslexics are able to encode and recall sequences items, they are not able to extract the inherent regularities of these sequences due to an implicit learning deficit. The authors suggest that this deficit should account for the difficulties in reading acquisition presented by dyslexics, because they will fail to acquire the statistical rules in grapheme-phoneme correspondences.

These studies (Pavlidou et al., 2010; Pavlidou et al., 2009), although innovative and revealing, present some issues that prevent us from drawing firm conclusions about the dyslexics implicit learning. In the second study, although Pavlidou and colleagues (2010) found differences between groups in the grammaticality classification test, the performance of the typically developing children was bellow what is expected when implicit learning is achieved in AGL tasks. These results indicate that both studies may suffer from a lack of sensitivity because it used a limited design with only one acquisition session. An extended period of exposure to the grammatical items should improve acquisition and therefore regularities of the underlying grammar will be more easily implicitly learned (Forkstam et al., 2008). In addition, performance at an individual level should be considered, since there may be interesting differences that might not be visible in a group analysis.

Given the general paucity of research and the inconsistent findings of studies of implicit learning in dyslexia, the aim of the present study is to investigate the implicit learning abilities in dyslexics, using a more complex implicit learning task adapted to children with dyslexia. We will therefore use the artificial grammar learning paradigm, in line with Pavlidou's studies (Pavlidou et al., 2010; Pavlidou et al., 2009), with some modifications in order to maximize the exposure to the sequence regularities and diminish factors such as slower performance that might prevent implicit learning form occurring.

OBJECTIVES

To date, there is no consensus about whether or not dyslexics present an implicit learning deficit. We aim to address this issue with an artificial grammar learning task designed for children, using several acquisition sessions in order to promote successful acquisition in all children. If dyslexic children have an implicit learning deficit, we expect them to show no or little classification performance, indicating a disrupted learning ability, compared to normal children. In addition, we intend to investigate how implicit learning is reflected in the light of other cognitive skills, such as reading and writing. For this purpose, we investigate the relationship between the complementary tasks (described bellow) and the implicit learning task. If dyslexics have an implicit learning deficit that underlies the reading ability, an association between these skills is to be expected.

METHODS AND MATERIALS

Participants

All participants were recruited from elementary schools (2^{nd} – 4^{th} grade). Informed consent was obtained from all the participants and their parents. All subjects had normal or corrected to normal vision. Of twenty-four children with either a formal dyslexia diagnosis or suspected dyslexia by the teachers, only fourteen (8 male and 6 female, mean age ± SD = 9.7 ± 1.1 years; mean grade ± SD = 3.2 ± 0.8) met the inclusion criteria for dyslexia. The inclusion criteria were: absence of neurological or emotional problems; normal-range intelligence as measured by the Raven Coloured Matrices (Raven, Raven, & Court, 2009); reading scores below 25% on the *Teste de Idade de Leitura* – TIL, a Reading Age Test (Santos & Castro, 2010); reading abilities significantly below grade mean level in the 3DM reading and spelling tests (Reis et al., 2011 – specifically, subjects who had either a reading speed score ≥ 1.25 SD below the grade mean or a reading speed score ≥ 0.75 SD below the grade mean combined with a spellings score ≥ 1.25 SD below the grade mean) – all tasks are explained bellow.

Two control groups were selected to match the dyslexic group – one group matched for age (age-matched control) and the other matched for reading skills (reading-matched control). The age-matched control group was selected, whenever was possible, from the same classroom as the dyslexic children and were classified by their teachers as average pupils. From twenty-six children initially selected, only ten (5 male and 5 female, mean age ± SD = 9.2 ± 0.7 years; mean grade ± SD = 3.2 ± 0.9) were selected to match the dyslexia group (specific inclusion criteria: reading scores above 25% in TIL (Santos & Castro, 2010) and reading abilities significantly within or above the grade mean level in the 3DM reading and spelling tests (Reis et al., 2011)).

The reading-matched control group was selected, whenever was possible, from the same school as the other groups and children were chosen by the teachers as students from the first grade who were already able to read, typically average or above average students. From nineteen initially selected, fourteen (7 male and 7 female, mean age ± SD = 6.9 ± 0.3 years; mean grade ± SD = 1.0 ± 0) were selected to match with the dyslexia group (same inclusion criteria as for the age-matched control group). The inclusion of a reading-matched group is important because it allows us to exclude that a given deficit is simply a consequence of the less reading experience in dyslexic children (e.g., “trivial” developmental delay).

The dyslexic group differed significantly on the reading and writing scores from the age-matched control group (all p’s < .01), but not from the reading-matched control group (p = .24 and p = .82, respectively). The dyslexic and the age-matched control group did not differ significantly in age or grade (p = .20 and p = .99, respectively), while both groups differed significantly in age and grade from the reading-matched control group (all *p*'s < .01).

Complementary tasks

All groups were tested for reading, spelling and cognitive abilities in order to characterize the sample and confirm the dyslexics' deficits. For this, we selected four tasks from the Differential Diagnosis Dyslexia Battery (3DM – Blomert & Vaessen, 2009), adapted for the Portuguese population (Reis et al., 2011). These 3DM tasks were displayed on a computer screen, using the Presentation software (version 13.0; http://nbs.neurobs.com/presentation). We also used two tasks form the Wechsler Intelligence Scale for Children (Wechsler, 2006), a nonverbal Intelligence Quotient (IQ) task (Raven et al., 2009) and a reading age task (Santos & Castro, 2010). All tasks are explained below, together with the groups' results.

Word reading task - The 3DM reading task includes three different word lists: high-frequency words, low-frequency words, and pseudowords. Each list is composed by 75 stimuli distributed on five sheets of increasing difficulty in length and syllabic structure. From each list, the child reads aloud as many words as possible for 30 seconds. Reading fluency is computed as the number of correctly read words per second.

Reading age task - The *Teste de Idade de Leitura* (TIL – Santos & Castro, 2010) involves decoding and comprehension skills. The child reads incomplete sentences and selects the final word out of five possibilities that will give the correct intention. The task lasts for five minutes and results in a standardized percentile over age.

Spelling task - In this 3DM task, the child listens to a word and sees the same incompletely written word. Among four alternatives, the child has to choose the correct portion that completes the visual incomplete word. This task is composed by 96 incomplete words with increased difficulty in length and syllabic structure. The frequency, number of syllables, syllabic structure and omitted portion of the word is controlled and counterbalanced over the task. Accuracy is calculated as the percentage of correct words.

Phoneme deletion task - Phonological awareness is tested using the 3DM phoneme deletion task. In this task, forty-four pseudowords are presented aurally via headphones while the child is instructed to delete a phoneme and provide the remaining pseudoword. The pseudowords are manipulated in terms of word length (monosyllabic and disyllabic), syllabic structure (with and without consonant clusters) and position of the phoneme to be deleted (beginning, middle or end). Accuracy is calculated as the percentage of correct items.

Rapid Naming task - The 3DM rapid naming repetition task is based on the classical paradigm by Denckla & Rudel (1976) and it is divided in 3 sub-tests: letters, digits and objects. Each sub-test is composed of sheets of 15 items each (five letters, digits, or objects repeated three times), that are presented two times, with a different order of items. The children are instructed to name visually presented letters, digits, or objects as fast as possible. The number of correctly named items per second is used as a measure of naming speed.

Vocabulary task - The Vocabulary subtest of the WISC (Wechsler, 2006) is used in order to assess word knowledge, independently reading and writing skills. In this task the children has to orally define a set of words.

Digit span task - Phonological short term memory is assessed using the Digit Span task from the WISC (Wechsler, 2006). In this task, children are instructed to orally repeat digit sequences, in the same order or in the inverse order.

Coloured progressive matrices (parallel form) - Nonverbal IQ is assessed with the Raven's Progressive Matrices (Raven et al., 2009), a measure of abstract perceptual reasoning. This test is composed of figures that the child has to complete with one of the six available options. The test is presented in increasing order of difficulty. After two practice items with feedback, the child completes 36 items.

In all complementary tasks, with the exception of the IQ test, the dyslexic group showed significantly lower scores than both control groups, as expected (see table 1 - it is worth noticing that in the reading and spelling tasks the reading-matched control group performed at the same level as dyslexic group did, but when scores were converted into z-scores with reference to normative data, differences emerged).

TABLE 1. Group performance on the complementary tasks (mean ± SD). * = mean scores significantly different from dyslexic group mean scores (*p*'s < .01, except ** *p* < .05). Note: standardized values were used in all tasks except the reading age task (there were no available standardized values for the younger group).

	Dyslexic group	Age-matched control group		Reading-matched control group	
Word reading (z-scores)	-1.75 ± 0.41	0.97 ± 0.93	*	1.23 ± 0.61	*
Reading age (raw scores)	23.61 ± 11.47	72.50 ± 17.88	*	19.44 ± 8.44	
Spelling (z-scores)	-1.38 ± 0.71	0.50 ± 0.63	*	0.92 ± 0.50	*
Phoneme deletion (z-scores)	-1.41 ± 0.47	0.64 ± 0.75	*	0.69 ± 0.48	*
Rapid naming (z-scores)	-1.06 ± 0.72	0.99 ± 0.71	*	0.84 ± 0.63	*
Vocabulary (standardized values)	8.43 ± 2.44	11.20 ± 3.74	**	12.57 ± 2.10	*
Digit span (standardized values)	5.50 ± 1.99	8.80 ± 2.10	*	9.36 ± 2.65	*

Artificial grammar learning task

The artificial grammar learning task used in this study was the result of five previous pilot studies, where the stimuli were manipulated in order to provide the conditions for the children to show successful implicit acquisition. In these pilot studies, the length of sequences, type of symbols and the acquisition task appearance were investigated. In total, twenty-eight normal children participated in these pilot studies.

The final version of the stimulus material includes one acquisition set and one classification set. Using a regular grammar defined by the finite-state generator described in Figure 3, we generated the complete set of grammatical (G) stimulus sequences with a length of 2 to 7 elements from the symbol alphabet with coloured geometrical forms (green triangle, yellow square, red circle, blue diamond; see Figure 3). The geometrical forms and colour were used in order to facilitate acquisition in children and also be suitable for dyslexic children.

In order to quantify differences in subsequence familiarity between acquisition items and test items, associative chunk strength (ACS) was calculated for each item. The ACS measure captures the frequency distribution of 2- and 3-letter chunks for both terminal and complete sequence positions (Knowlton & Squire, 1996; Meulemans & Van der Linden, 1997).

Of the total set of grammatical sequences, 38 items were included in the acquisition set using an iterative random procedure. The acquisition set was selected to be comparable in terms of ACS familiarity to the complete set. Non-grammatical (NG) items were generated by switching symbols in two non-terminal positions from each remaining grammatical items, keeping the ACS score on par with its original template item. For the classification set, 20 grammatical/non-grammatical pairs were selected from the remaining items in an iterative random procedure, such that 10 items were similar in ACS to the acquisition set while 10 items showed a significantly lower ACS score. In this way, the classification set was organized in a 2x2 factorial design, with grammaticality (grammatical/non-grammatical) and ACS (high/low) as factors, including 10 sequences of each category: high ACS grammatical (HG), low ACS grammatical (LG), high ACS non-grammatical (HNG), and low ACS non-grammatical (LNG).

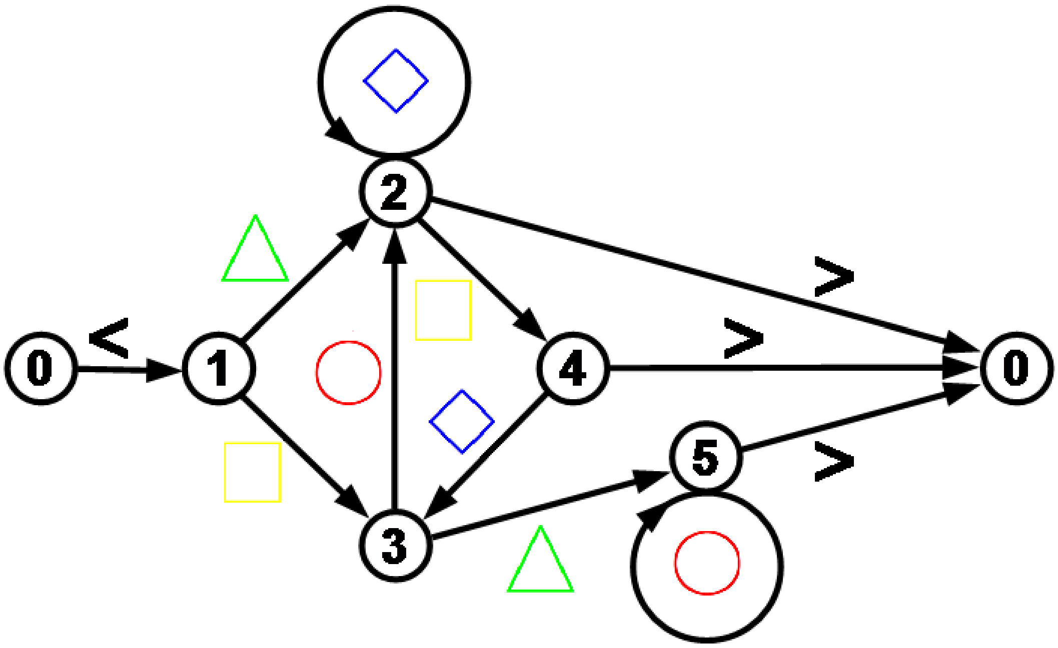

FIGURE 3. The transition graph representation of the regular grammar used in the present study. Sequences that follow the transitions in this graph are grammatical while sequences that do not are not.

Procedure

The experiment was divided in three sessions, conducted over three consecutive days. All tasks were presented visually on a portable laptop computer screen and responses were recorded using a *Cedrus RB series* response pad, connected to the laptop. All sessions started with a short-term memory cover task, the acquisition task. During the acquisition task subjects were exposed to and had to memorize grammatical sequences for a duration of 8 seconds each. After each sequence disappeared from the screen the subjects tried to reproduce the sequence, in a self-paced manner, using the response pad to type the symbols (one button per symbol). The presentation order was randomized for each acquisition session and each session lasted for approximately 20 minutes.

After each acquisition task, the subjects were interviewed in order to assess the level of experienced difficulties in fulfilling the acquisition task and whether they notice any pattern or rule system. All subjects reported that the task was relatively easy, with the exception of a few more longer and complicated sequences and none reported to have noticed any rules or patterns underlying the sequences.

On the third day, after the short-term memory task, subjects engaged in a non-sense distracting task, in order to divert attention from the acquisition task. Subsequently, the participants' knowledge about the underlying grammatical structure was tested using grammaticality classifications. The subjects were informed about the existence of a complex set of rules that underlies the acquisition sequences structure and were instructed to classify new sequences (20 grammatical and 20 non-grammatical) to have a good or bad similarity (i.e., grammatical or non-grammatical) with the acquisition sequences. Each sequence was presented on the screen for 3 seconds followed by a grammaticality judgement (forced yes/no choice) using the response pad, in a self-paced manner. The subjects were instructed to base their decision on their immediate intuition and to avoid any attempt to explicitly analyse the sequences. The presentation order was randomized for each classification test and lasted for approximately 10 minutes. The session finished with a subject interview in order to assess their explicit knowledge about any pattern or rule system, including a test to reproduce grammatical sequences using cards with the same symbols which were previously presented.

The complementary tasks were evenly distributed over the three days of testing, except in the case that children were too tired and the tasks were instead administered during a subsequent day. All sessions were conducted in the schools of the children, in a quiet and undisturbed room, separated from the other children and during normal school hours.

RESULTS

Acquisition analysis

All analysis presented were performed using the statistical software package SPSS and an overall significance level of $p < .05$ was used. The accuracy in the acquisition task was analysed with a repeated-measures ANOVA with the group as between-subject factor (dyslexics/age-matched control/reading-matched control) and the acquisition days as within-subject factor (day 1/day 2/day 3). The results showed a main effect of group ($F(2,33) = 9.89$, $p < .00$). A *post-hoc* analysis (Tukey HSD) showed that the age-matched control group acquisition performance (% mean ± SD = 57.9 ± 7.99) was better than the dyslexic (% mean ± SD = 41.07 ± 3.54) and reading-matched control group (% mean ± SD = 35.41 ± 5.7) (all *p*'s < .001). The performance of the dyslexics and reading-matched controls did not significantly differ from each other on the three acquisition sessions. A main effect of acquisition day was also observed ($F(2,66) = 30.36$, $p < .001$). A Tukey HSD *post-hoc* comparison showed an increase in the acquisition performance over the three days (all *p*'s < .001). The interaction between acquisition day and group was also significant ($F(4,66) = 2.61$, $p = .04$). The *Post-hoc* analysis revealed that the age-matched and the reading-matched control groups showed a significant increase in the acquisition performance between the first and last day (all *p*'s < .001), which was not observed in the dyslexic group.

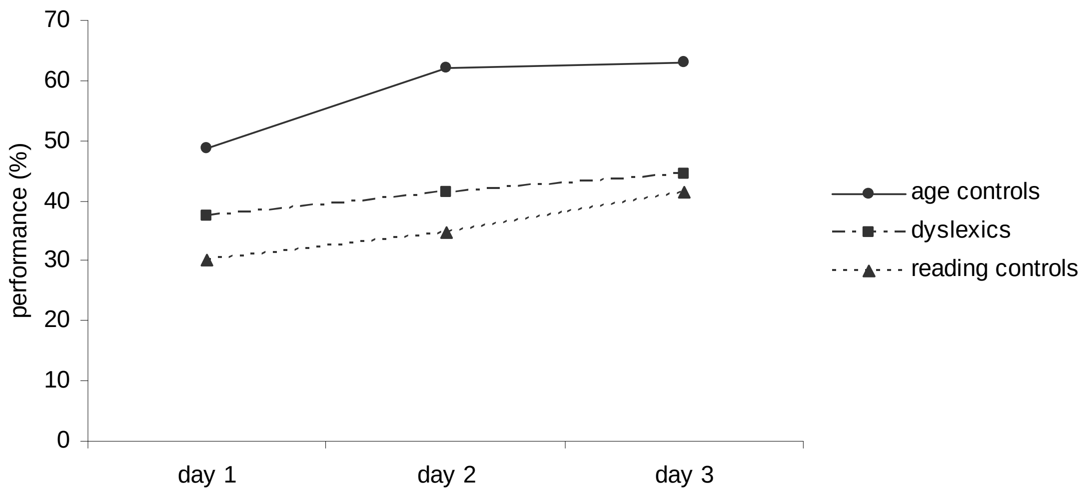

FIGURE 4. Acquisition performance (mean percentage of correct responses in the short-term memory task) per group.

Classification performance: endorsement rates

Performance on the classification test was analysed in terms of endorsement rate (% of strings perceived as grammatical - cf. Forkstam et al., 2006). In order to analyse the performance of each group in the classification test, we performed separate *t*-tests to compare the performance in grammatical (G) vs. non-grammatical (NG) sequences and in high ACS (H) vs. low ACS (L) sequences. In all groups, the comparison G vs. NG did not reach significance (all p's $> .08$). In contrast, all groups showed a significant differences in the H vs. L comparison (dyslexic group: t (13) = 3.14; $p = .008$; age-matched control group: t (9) = 2.41; $p = .04$; reading-matched control group: t (13) = 4.25; $p = .001$) (Figure 5). The comparison between grammatical and non-grammatical sequences also reached significance within the high ACS sequences (HG vs. HNG) in the dyslexic group (t (13) = 2.11; $p = .05$) and in the age-matched control group (t (9) = 2.37; $p = .04$) (Figure 6).

To explore the difference in the overall performance of the groups more thoroughly a repeated-measures ANOVA with grammaticality (grammatical/non-grammatical) and ACS (high/low) as within-subject factors and with the group as between-subject factor (dyslexics/age-matched control/reading-matched control) was performed. This analysis showed significant main effects of grammaticality ($F(1,35) = 9.04$, $p < .01$), ACS ($F(1,35) = 30.16$, $p < .01$) and a significant interaction between grammaticality and ACS ($F(1,35) = 8.91$, $p < .01$), as previously observed. There are no significant effects of group, interactions between group and grammaticality or ACS or interactions between grammaticality, ACS and group (all p's $> .13$). These results suggest that dyslexic children performed similarly to both control groups. Thus, all groups acquired knowledge of the underlying grammar to a similar degree after three days of implicit acquisition.

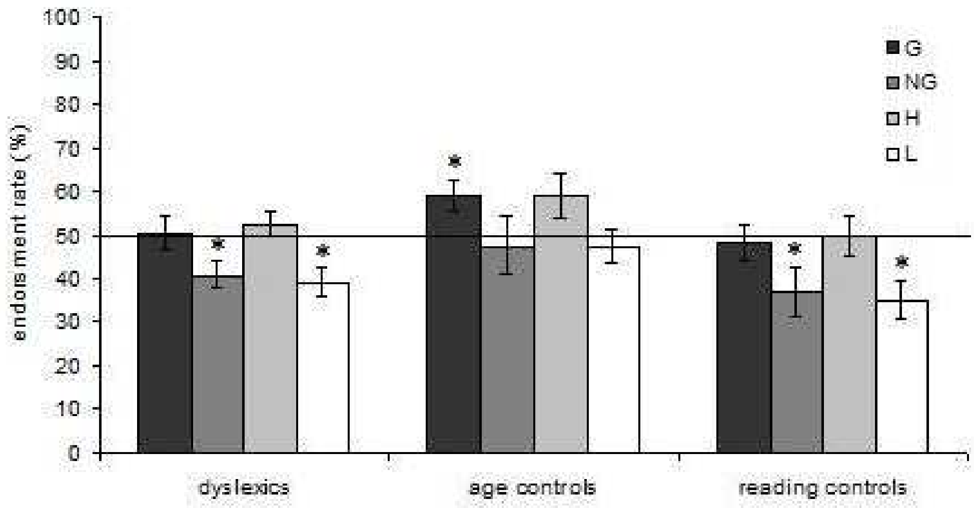

FIGURE 5. Endorsement rates over grammaticality and ACS as main factor categories. (G: Grammatical sequences; NG: Non-Grammatical sequences; H: High ACS sequences; L: Low ACS sequences). Error bars correspond to standard error of the mean. * = significantly different than 50% (chance level), $p < .05$.

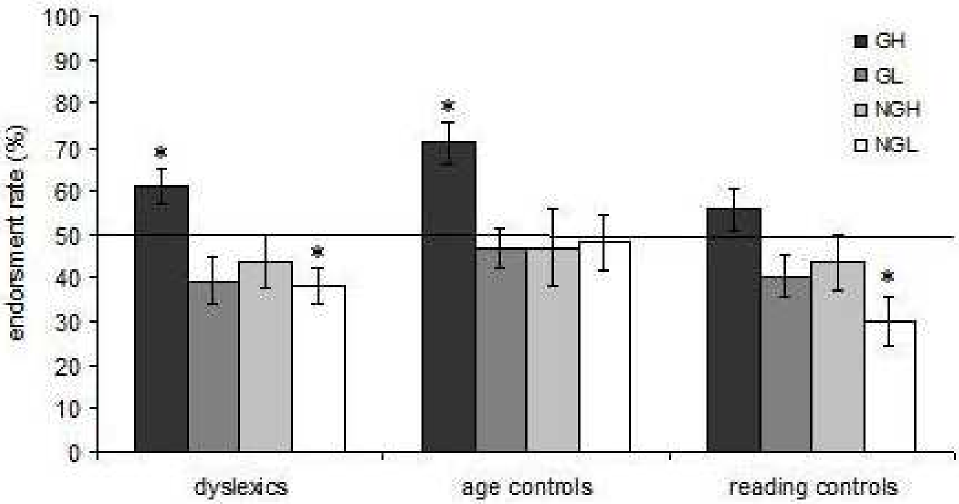

FIGURE 6. Endorsement rates over grammaticality and ACS levels (GH: Grammatical High ACS sequences; GL: Grammatical Low ACS sequences; NGH: Non-Grammatical High ACS sequences; NGL: Non-Grammatical Low ACS sequences). Error bars correspond to standard error of the mean. * = significantly different than 50% (chance) , *p*'s < .05.

Signal detection analysis

The endorsement rate analysis is not clear in showing acquisition and this might be due to the fact that some subjects were performing the classification task in a reverse way (i. e. rating the grammatical sequences as non-grammatical and vice-versa). Considering this, we also analysed the classification test performance in terms of ability to discriminate grammatical from non-grammatical sequences, i.e., a discrimination index (d’). Some subjects presented negative d’ (a preference for non-grammatical over grammatical sequences). Since we are interested in each subject’s ability to discriminate non-grammatical from grammatical sequences, it does not matter if they prefer grammatical or non-grammatical sequences. All d’ were thus converted to absolute values. An ANOVA with d’ for grammaticality as within-subject factor and with the group as between-subject factor was performed. The discrimination index for grammaticality did not differ significantly between groups ($F(2,35) = 0.63$, $p = .54$) (Figure 7). In other words, the groups showed little differences in the ability to discriminate between grammatical and non-grammatical sequences.

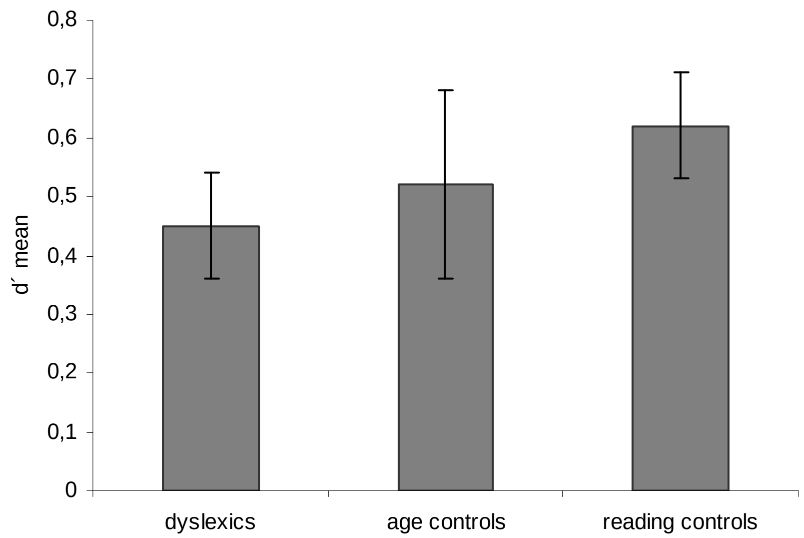

FIGURE 7. Group averages for the absolute d’ value over grammaticality. Error bars correspond to standard error of the mean. All group averages are significant (all *p*’s <.009).

When investigating this discrimination analysis split over high and low ACS, d’ means remained non-significant between groups (Figure 8; grammatical high ACS: $F(2,35) = 0.23$, $p = .79$; grammatical low ACS: $F(2,35) = 0.57$, $p = .57$). Thus, the groups discriminated, to a similar degree, between grammatical and non-grammatical sequences both in sequences with high and low ACS. In a similar analysis over the absolute d’ value over associative chunk strength, there were no differences between groups regarding their sensitivity to ACS status ($F(2,35) = 0.27$, $p = .77$) (Figure 9).

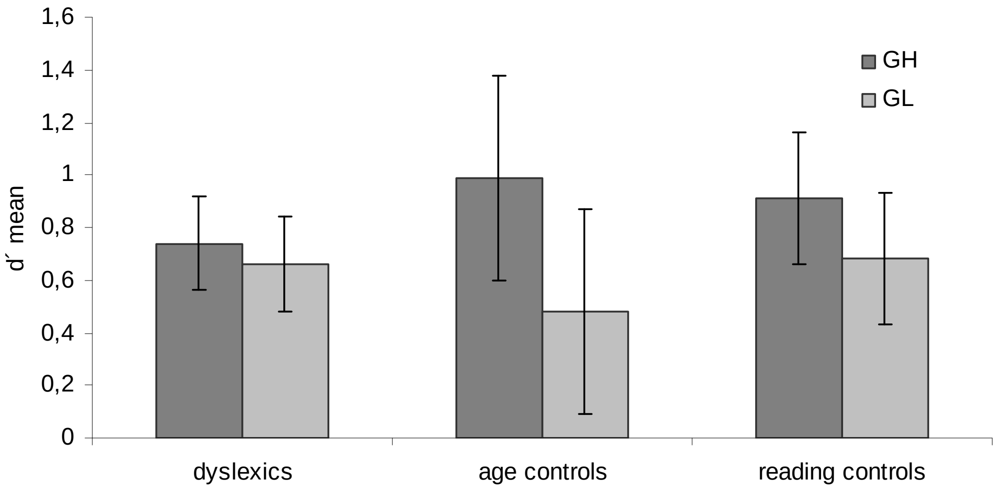

FIGURE 8. Group averages for the absolute d' value over grammaticality. (GH: Grammatical High ACS sequences; GL: Grammatical Low ACS sequences). Error bars correspond to standard error of the mean. All group averages are significant (all *p*'s < .03).

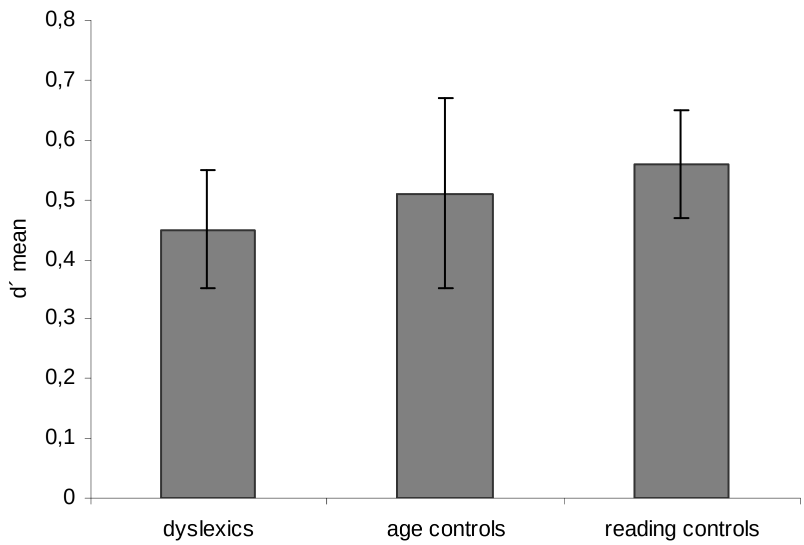

FIGURE 9. Group averages for the absolute d' value over associative chunk strength (for the purpose of the analysis, the low grammatical sequences were perceived as false alarms). Error bars correspond to standard error of the mean. All group averages are significant (all *p*'s < .03).

Subject analysis

Folia and colleagues (2008) suggested that a null-finding in a group analysis may reflect a lack of statistical power due to small study samples. To avoid this and because a group analysis may conceal relevant individual aspects, we investigated the individual performance of the subjects (Table 2). Four dyslexic children present high grammatical d' values (subjects 19, 27, 61 and 67) as well as endorsement rates, indicating that these subjects were able to discriminate between grammatical and non-grammatical items, regardless of ACS status. Four subjects in the age-matched control group (subjects 1, 4, 31 and 66) and four subjects in the reading-matched control group (subjects 7, 8, 57 and 63) also performed significantly. These results show that at least some dyslexics are able to acquire a grammar in an implicit fashion, and that as a group the dyslexics perform at the same level as normal children do, supporting the previous group analysis.

Relationship between implicit learning and complementary tasks

In addition to the group and individual subject analyses reported above, following other studies (eg. Howard et al., 2006; Waber et al., 2003), we performed a series of correlations to examine the relationship between implicit sequence learning and the reading, writing, rapid naming, phonological awareness, and working memory (described in the methods section).

We performed a separate analysis for each group (dyslexics, age-matched control and reading-matched control group), where the discrimination index (d') for grammaticality was correlated with the complementary measures scores. This revealed significant positive correlations between the working memory task (digit span) and the d' for grammaticality in both control groups (age-matched control group: $r = 0.81$, $p < 0.01$; reading-matched control group: $r = 0.54$, $p = 0.04$). We then performed a new group analysis, taking in account this measure. An ANCOVA with the d' for grammaticality as dependent variable, the group as fixed factor and the digit span as covariate did not show any significant differences between groups ($F(2,34) = 1.25$, $p = .30$). This result indicate that, despite grammatical d' of the groups correlate differently with digit span, this did not influence the group results.

A positive correlation was also observed between the phonological awareness task (phoneme deletion) and the d' for grammaticality only in the dyslexic group ($r = 0.59$, $p = .03$). However in an ANCOVA with the d' for grammaticality as dependent variable, the group as fixed factor and phoneme deletion as covariate, no significant differences between groups were observed ($F(2,34) = 0.46$, $p = .64$). Despite an absence of any differences between groups, this correlation might suggest that reading related skills (in this case, phonological awareness), is associated to implicit learning.

Subjects interview

In order to assess if subjects were using or aware of any rule system underlying the sequences, they were interviewed at the end of the acquisition and classification tasks. The majority of subjects realized that sequences always started with triangles or squares, which was true. Three subjects from the age-matched control group also reported that it was not allowed to repeat these shapes in a sequence, which was also true. In addition, subjects were asked to reproduce grammatical sequences with the aid of cards with the symbols that had been previously presented. Two dyslexic subjects were able to reproduce 4 and 6 correct grammatical sequences, respectively; two subjects from the age-matched control group managed to reproduce 5 and 9 correct grammatical sequences, respectively; and two subjects from the reading-matched control group reproduced 5 and 6 correct grammatical sequences, respectively (see Table 2). The remaining subjects accomplished at most three correct grammatical sequences. However, these reproductions did not correlate with the grammatical discrimination index, d’ (r = 0.28, p = .08). We therefore argue that, although subjects were aware of a few salient characteristics, they were not able to reproduce the more complex set of rules that generate the sequences, and in this sense their performance in the classification task was dependent on the previously acquired implicit knowledge, independently of any valid explicit knowledge of the rules.

TABLE 2. Endorsement rates and d' by subject (Dys = dyslexic group; AC = age-matched control group; RC = reading-matched control group; GH = grammatical, high ACS; GL = grammatical, low ACS; NGH = nongrammatical, high ACS; NGL = nongrammatical, low ACS; d'_G = d' for grammaticality; N G-sequences = number of grammatical sequences reproduced by the subjects with the aid of symbol cards).

Subj	GH	GL	NGH	NGL	d'_G	N G-sequences
Dys_13	50,00	40,00	40,00	50,00	0,00	0
Dys_14	80,00	10,00	30,00	20,00	0,55	6
Dys_16	60,00	50,00	70,00	20,00	0,25	1
Dys_17	60,00	60,00	60,00	40,00	0,25	2
Dys_19	80,00	60,00	40,00	30,00	0,91	4
Dys_22	60,00	30,00	90,00	40,00	-0,51	0
Dys_25	50,00	50,00	40,00	70,00	-0,13	2
Dys_26	50,00	20,00	60,00	40,00	-0,39	2
Dys_27	70,00	50,00	10,00	40,00	0,93	1
Dys_28	50,00	20,00	40,00	40,00	-0,13	1
Dys_60	33,33	0,00	30,00	30,00	-0,27	0
Dys_61	90,00	50,00	22,22	60,00	0,72	0
Dys_67	70,00	50,00	20,00	22,22	1,06	0
Dys_68	50,00	60,00	60,00	30,00	0,25	3
AC_01	50,00	50,00	10,00	20,00	1,04	9
AC_04	60,00	60,00	80,00	90,00	-0,78	1
AC_05	60,00	40,00	40,00	30,00	0,39	3
AC_30	80,00	40,00	80,00	50,00	-0,13	3
AC_31	100,00	60,00	20,00	30,00	1,52	5
AC_39	60,00	20,00	10,00	60,00	0,13	1
AC_40	70,00	40,00	70,00	40,00	0,00	3
AC_45	70,00	70,00	60,00	60,00	0,27	0
AC_65	70,00	40,00	70,00	50,00	-0,13	0
AC_66	90,00	50,00	30,00	50,00	0,78	1
RC_07	50,00	40,00	100,00	60,00	-0,97	0
RC_08	60,00	50,00	40,00	10,00	0,80	5
RC_09	60,00	33,33	50,00	20,00	0,32	6
RC_10	40,00	30,00	20,00	10,00	0,65	3
RC_34	60,00	60,00	50,00	40,00	0,38	1
RC_35	50,00	40,00	40,00	40,00	0,13	1
RC_46	50,00	70,00	30,00	50,00	0,51	2
RC_47	60,00	30,00	40,00	20,00	0,40	3
RC_48	60,00	50,00	50,00	20,00	0,51	3
RC_53	100,00	60,00	70,00	60,00	0,46	3
RC_54	20,00	0,00	30,00	10,00	-0,44	0
RC_57	80,00	40,00	10,00	10,00	1,53	3
RC_63	40,00	30,00	10,00	10,00	0,90	2
RC_64	50,00	30,00	70,00	60,00	-0,64	1

DISCUSSION

The purpose of this study was to investigate whether, and to which degree, dyslexic children can accomplish implicit acquisition in an artificial grammar learning paradigm, designed to suit the requirements of children between 6-10 years old. Our results revealed no differences between dyslexics and any of the control groups (age-matched and reading-matched control) in the classification test, indicating that the different groups of children acquired the stimulus regularities at a similar level. Moreover, the ability to discriminate between grammatical and non-grammatical sequences (grammatical discrimination index) was also very similar between groups.

Interestingly, the reading-matched control group (the youngest group) performed at the same level as the age-matched controls and the dyslexics (the older groups). These results support the notion that this kind of implicit learning abilities are in place early in development and that there are no significant age-related differences at time of early school age (see, for example, Meulemans, Van der Linden, & Perruchet, 1998). However, all groups performed bellow normal levels in young adults in the classification test. This may be due to constrains in the task (such as long sequences or short periods of acquisition). The balance between creating an easy task that suits children and keeping it complex enough to avoid explicit knowledge to take part in the sequence acquisition is difficult to obtain. Despite several pilot studies to find this trade-off, the relatively low level of performance, specifically in the age-matched control group, indicate that we did not fully reach this goal. Nevertheless, the individual analysis allowed us to observe that some dyslexic children did reach high levels of grammatical discrimination on par with the age-matched and reading-matched control groups. Additionally, the post-experimental interviews indicated that subjects did not acquire explicit knowledge of the underlying grammatical system. We therefore conclude that implicit learning of artificial grammars is intact in dyslexic children. These results confirm the Russeler, Gerth and Munte (2006) predictions. In their study, the authors showed that adult dyslexics were able to learn an implicit artificial grammar and predicted that these results could be extended to dyslexic children.

Interestingly, our results clearly diverge from the results of Pavlidou and colleagues studies, using a similar paradigm (Pavlidou et al., 2010; Pavlidou et al., 2009). Their results showed that while dyslexic children were performing at chance levels, the typically developing children were able to successfully distinguish between grammatical and non-grammatical items. The authors then claimed, following their results, that dyslexic children are not able to abstract implicit knowledge, that is, to extract the regularities of highly complex structured patterns such as AGL, due to an implicit learning deficit (Pavlidou et al., 2010). However, there are some issues with the Pavlidou's studies that may prevent dyslexic implicit acquisition. Both studies presented a lack of sensitivity, which can be observed in the low performance of the control group. The group differences that emerged in these studies could be attributable, not to a dyslexic implicit learning deficit, but to an inefficient acquisition process with the implication that dyslexic children did not extract the regularities of the task or might had lead to a deficient consolidation of these regularities. It has already been shown that dyslexics may need different strategies to cope in implicit learning tasks. For example, Kelly and colleagues (2002) and Roodenerys and Dunn (2008) showed that, although dyslexics performance in a SRT task was at the same level as normal readers, they presented slower responses. In the studies by Pavlidou and colleagues (Pavlidou et al., 2010; Pavlidou et al., 2009) the limited exposure to grammatical items in only one acquisition session and immediate testing may lead to poor consolidation processes already described as important for an optimal performance in artificial grammar learning (Forkstam et al., 2008). Moreover, their group analysis may be concealing individual achievements (that is, some dyslexics could have reached higher levels of performance in the classification test that cannot be accessed by blending this results with the results of other subjects with lower scores). An analysis over individuals might have revealed that some dyslexics could have the implicit learning abilities intact. This was the case in the study of Stoodley and colleagues (2006). In this study, although the authors found a significant difference in performance between a group of dyslexics and a group of normal readers, some dyslexics were able to perform at the same level as the normal readers group. Such finding lead the authors to conclude that they could be in a presence of a high level of ability in their particular dyslexic group and that this fact could also reflect the general heterogeneity of deficits found in dyslexia (Stoodley et al., 2006).

It is possible that the different findings observed on implicit learning in studies of dyslexics may be due not only to the wide variation of tasks (with different stimuli presentation, different length of the sequences, different kind of response and consequently different procedures), as some authors propose (see, for example, Howard et al., 2006; Jiménez-Fernández et al., 2010; Russeler et al., 2006), but also due to differences in sample characteristics. The inclusion criteria used for the dyslexia group is often different (or not reported fully) from one study to another, and variations within the dyslexia group are frequently not further investigated. These differences among dyslexics might account for some of the differences encountered in these studies, as well as this one. Future studies using a larger sample of dyslexics, a more detailed assessment of their deficits and including individual analysis could clarify this issue.

In addition to investigate whether the dyslexics have an implicit learning deficit or not, we examined the relationship between implicit sequence learning and other cognitive measures to see if this relationship differed over groups. We found a significant positive correlation between the grammatical discrimination index and the working memory task in both control groups. In the dyslexic group this correlation was not significant. Conway, Bauernschmidt, Huang, and Pisoni (2010) suggested that although the ability to encode and hold a series of items in immediate memory is necessary to learn a sequence structure, this is not sufficient, and a well-functioning mechanism involved in learning the underlying regularities is also needed. Furthermore, the authors propose that smaller memory capacities may actually be beneficial for learning complex input because it acts as a filter to reduce the complexity of the problem space, making it more manageable (Conway et al., 2010). In this sense, the immediate memory could aid the sequence learning in both directions: for the controls, it helps to encode and hold the sequence items, improving the sequence structure learning; for the dyslexics, a lower memory capacity (as in our study – see Table 1) constrain them to transform the sequences into more manageable units which might aid the acquisition process. This would explain why there are not differences between groups in the discrimination index, despite this index correlate differently with the memory capacities of dyslexics and control groups.

The grammatical discrimination index was significantly correlated with the phoneme deletion task in the dyslexic group only. Moreover, the dyslexic group presented clear deficits in the phoneme deletion task (86% of the sample presented at least one standard deviation below the mean in this task). This result is difficult to interpret in the light that reading abilities are not supposed to be influenced by implicit learning and that the phoneme deletion task is a phonological awareness task that is typically associated with reading abilities and predicts reading competence (for a review see Kirby, Desrochers, Roth, & Lai, 2008). However this might indicate that there are different implicit learning nuances within dyslexics, and that a subgroup of dyslexics do present implicit learning deficits. Further investigation could account for these differences amongst dyslexics and if there are dissimilar implicit learning abilities that accompany these differences.

To summarize, the present study showed that dyslexic children were able to extract the implicit regularities of an artificial grammar to a similar degree as normal children. We suggest that reading instruction and remediation programs can take advantage of the preservation of implicit learning abilities in dyslexic children, exploiting this capacity to aid explicit processes in reading acquisition.

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