Implicit Motor and Language Learning in Developmental Dyslexia

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Linguistics: The Study of the Language Faculty

Utrecht University

Master Thesis

January 2013

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Acknowledgements

The writing of this thesis could not have been accomplished without the help and support of my supervisors, friends, and family. First of all, I would like to thank Nadya Goldberg and Gaetano Fiorin for supporting me in every phase of bringing about this thesis (even when you were not in the country). Thank you for answering all my questions and for your constructive feedback on my work. Thanks also to Annemarie Kerkhoff for your help and optimism in times of crisis.

A big thank you to my cousin Dawa Ometto who wrote several scripts we used for data analysis and to prepare stimuli sets for the artificial grammar learning task. You saved me many days (if not weeks) of tedious work! I would also like to thank Theo Veenker for writing the scripts for our tasks and for continuing to help us with the many changes we kept making.

Thank you Melle Eshuis, Dawa Ometto and Alexia Guerra Rivera for volunteering to participate in one of many pilot experiments and for being great friends.

Furthermore, I would like to thank Jakub Dotlacil for his lesson in statistics, his answers to my questions and for convincing me to start learning how to use R as soon as possible.

Frank Wijnen, thank you very much for giving me the opportunity to partake in this research project and for your constructive feedback on the prefinal version of this thesis.

I would like to thank my parents for their love and patience during times of stress or procrastination. Thanks to my father for always taking the time to answer any question (spelling related or not), and to my mom for your editing advice.

Last but not least, a big thank you to my boyfriend Joost for his never ending enthusiasm and for making sure I celebrated every single possible achievement (‘juichmomentje’), and to the rest of the van der Hammen family for your support, for many coffees and for your cheerfulness while I was finishing this thesis in between long cross country skiing trips, snow scooter safaris and reindeer sled rides in Lapland.

Abstract

Traditionally, Developmental Dyslexia is considered to be a disorder of language, but besides language problems, motor skill problems have been found in developmental dyslexics as well. This study was aimed at evaluating whether the difficulties dyslexics experience in the language and motor domain can be accounted for by one underlying domain general deficit in implicit learning. It was assessed whether 1.) developmental dyslexics show evidence of poor implicit learning in both the motor and language domain, 2.) but not of poor explicit learning, and whether 3.) implicit motor and language learning skills are associated within participants. 27 adult dyslexics and 27 age-matched controls performed an artificial grammar learning task, an implicit serial reaction time task and an explicit serial reaction time task.

No impairments in implicit learning were found in the dyslexic group as compared to the control group on artificial grammar learning or in learning in the implicit serial reaction time task. Also, no significant difference was found between the performance of dyslexics and controls on the explicit serial reaction time task. Performance on the artificial grammar learning task and on the implicit serial reaction time task were not correlated. Even though no significant impairment in implicit learning was found in the dyslexic group, there were indications that dyslexics did experience difficulty with some of the tasks. It remains unclear whether the difficulties dyslexics seemed to have were caused by a mild deficit in implicit learning or by a deficit in a different cognitive construct. We suggest that sustained attention may have affected performance in our tasks. Further research should be aimed at disentangling the effects of implicit learning skill and sustained attention capacity.

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1 Introduction

Developmental dyslexia (DD) is defined as a specific learning disability of neurological origin. Individuals with developmental dyslexia have difficulties with accurate and or fluent word recognition and they also have poor spelling and decoding abilities despite adequate education and in the absence of other cognitive impairments. These difficulties are typically ascribed to a phonological deficit. As a result of their difficulties dyslexics may experience problems in reading comprehension and reduced reading experience that in its turn may impede vocabulary growth and gaining background knowledge (International Dyslexia Association, 2002). Researchers have not reached consensus on whether dyslexia is solely a disorder of language or whether a deficit in another domain or even a domain general deficit underlies the disability. In this study we will address this issue.

Many deficits have been hypothesized to cause developmental dyslexia. Broadly supported is the phonological deficit hypothesis of dyslexia (Ramus, 2003; Stanovich, 2001). According to this theory dyslexia is associated with rapid naming and verbal short term memory problems, and with reduced phonological awareness (Ramus, 2003). These phonological problems are thought to cause difficulties in grapheme-phoneme mapping. In other words, the correspondence between speech sounds of a phonemic category and letters is not adequately developed in dyslexia.

Another hypothesis is that dyslexics have a visual impairment (reduced motion sensitivity, unstable binocular fixations) making it difficult to process written words and letters (Stein, 2001). Stein (2001) suggests that the unstable binocular fixations are caused by impaired development of the visual magnocellular system. Furthermore, impaired development of cells that detect changes (similarly to magnocells in the visual domain) in sound frequency and amplitude may cause problems with phoneme distinctions.

The temporal processing deficit (rapid auditory processing) hypothesis is more general than the phonological deficit theory (Tallal, et al., 1996). This hypothesis assumes that the underlying deficit in dyslexia is in rapid auditory processing in the temporal domain. Dyslexics have difficulty processing short acoustic events and rapid changes in these events (Tallal, 1980). These difficulties are thought to cause poor development of the phonological system, which in turn results in problems with language and reading. The temporal processing deficit is supported by Tallal's (1980) finding that dyslexics' performance is impaired on auditory tasks like tone discrimination. Also, Tallal (1980) found a high correlation between errors made on a nonsense word reading test and errors made responding to rapidly presented auditory stimuli in a perceptual test.

Recently, non-perceptual problems have been reported to occur in dyslexia as well. For example, dyslexics can have motor problems such as with balance, peg moving and rapid pointing (for an overview see Stoodley & Stein, 2011). Dyslexics have also been found to have problems with skill automatization. Nicolson and Fawcett were the first to propose a deficit in automatization of skills, possibly independent of the modality, to play a role in dyslexia (1990). Skill automatization can take place under explicit conditions (learning how to drive a car with explicit instruction and by extensive practice becoming so fluent at the skill that no conscious control is necessary) or under implicit conditions (a child in the south of Spain will learn how to clap his hands on complex flamenco rhythms by practice without having been told explicitly on which beats to clap). Both the motor skills affected in dyslexia and the automatization of skills are thought to be supported by the cerebellum. Therefore, Nicolson, Fawcett and Dean proposed that the problems dyslexics have with motor skill, skill automatization and their phonological deficits is caused by an underlying impairment in implicit learning resulting from cerebellar abnormalities (2001).

Implicit learning is defined as the ability to learn without having the intention to do so, without being aware of the learning process and in such a way that the knowledge gained is difficult to express verbally (Cleeremans, Destrebecqz, & Boyer, 1998). The knowledge gained by implicit learning is part of the nondeclarative memory. Unlike recollection from declarative memory, one cannot consciously recollect and reason about information stored in nondeclarative memory. Nondeclarative memory can only be accessed through performance. Sometimes nondeclarative memory is referred to as implicit memory (e.g. in Squire & Zola-Morgan, 1991), but not all nondeclarative memory subtypes are necessarily implicit.

It has been suggested that impairments in implicit learning during development may play a causal role in the formation of a deficit in phonological awareness and in reading skill in dyslexics (Fawcett & Nicolson, 2004). Fluent reading is clearly a skill for which automatization is crucial. Besides the intuitive notion that automatization of phoneme and word recognition as well as automatization of stable binocular eye movements are needed for fluent reading, it has been suggested that implicit learning plays a role in the reading and spelling problems in dyslexia at an even more basic level. In early linguistic development, representations of phonemic categories are acquired implicitly. This process is thought to occur through analysis of distributional properties of sounds in perceived speech (see Kuhl, 2004). A deficit in implicit acquisition of phoneme categories can cause representations of phonemes to be impaired, which in its turn may cause the problems with reading and spelling (Wijnen, 2013).

There is evidence from behavioral studies, neuroimaging studies and biochemical studies suggesting that implicit learning is impaired in developmental dyslexia. Below, both types of evidence will be discussed. First, the two tasks that are used most often in studies assessing implicit learning skills, and that we will use in the present study, will be briefly described: The artificial grammar learning paradigm (Reber, 1967), and the serial reaction time task (Nissen & Bullemer, 1987). In the serial reaction time task (SRTT), implicit learning is tested in the sensorimotor domain, while artificial grammar learning (AGL) is linguistic in nature. However, both tasks might essentially assess the same domain general implicit learning skill.

In artificial grammar learning, participants are exposed to a stream of language stimuli generated by the rules of an artificial grammar. After this familiarization phase, participants are told that the stream of stimuli was generated according to a set of rules and they are asked to classify novel strings as grammatical or ungrammatical according to the grammar they had been exposed to in the familiarization phase.

In the traditional SRT task, participants are exposed to a fixed sequence presented visually. Participants are asked to respond by pressing a button corresponding to the position of each stimulus on the screen. Reaction times are measured throughout the task. As the participant learns the sequence, reaction times decrease. After the exposure to a series of fixed sequence blocks, a block with random sequences follows. The increase in reaction time in the random sequence block as compared to the fixed sequence block is taken to be a measure of implicit learning. The motor component in the SRTT exists of the sequence of motions the participant learns while responding to the perceptual sequence presented to them. Adaptations of the original SRTT include tasks in which fixed sequence and random blocks are alternated. This makes it possible to control for effects of fatigue. The increasing difference between reaction times in fixed sequence blocks and random blocks is take to reflect learning.

Neither in the SRTT nor in AGL do participants receive explicit instructions beforehand to look for a pattern in the stimuli, so that intentional learning and awareness of the learning process are avoided as much as possible. A study on implicit learning must always include a test to assess explicit knowledge. Artificial grammar learning and the serial reaction time task differ in that the former requires the participant to abstract a complex rule or a grammar from the input, while in the latter the participant often learns only one fixed sequence (Goldberg, n.d.).

In order to assess the implicit sensorimotor learning abilities of dyslexics many authors used adaptations of the serial reaction time task (SRTT) (Nissen & Bullemer, 1987). Stoodley, Harrison, and Stein (2006) for example tested implicit sensorimotor learning in dyslexic adults and age-matched controls using an SRTT. The authors found dyslexics to be impaired on this task (reaction times of dyslexics decreased less over the sequence blocks than reaction times of controls) as compared to the controls. However, not all dyslexics performed worse than the controls, suggesting that implicit sensorimotor learning may be affected to different degrees in subtypes of dyslexia. To assess the specificity of the implicit learning deficit in dyslexics, Stoodley, Ray, Jack & Stein (2008) tested implicit motor sequence learning ability in dyslexics, controls and 'garden-variety' poor readers. The authors found that the reaction time decreases from a random to a sequence block of controls and poor readers revealed good implicit learning of the sequence, whereas reaction times of dyslexics did not decrease significantly.

In Howard, Howard, Japikse, and Eden's (2006) study dyslexic and non-dyslexic adults were asked to perform two different types of implicit learning tasks: an adaptation of the SRTT with dependencies between non-adjacent elements and a spatial context learning task. The authors found that dyslexics were impaired on the SRTT but not on the spatial context learning task. This result indicates that whereas dyslexics have difficulty with implicit learning of temporal representations of sequential events, implicit learning in the spatial domain remains intact. Jiménez-Fernández, Vaquero, Jiménez, and Defior (2011) found similar results in children, and add that explicit sequence learning, unlike implicit sequence learning, was intact in children with developmental dyslexia.

Sperling, Lu and Manis (2004) on the other hand, found poor readers to have an impairment in implicit categorical learning without temporal dimension. Adult poor readers and controls were asked to categorize geometric shapes overlaid on a geometric background into either of two classes. The poor readers learned to categorize the shapes slower than controls in the implicit condition but not in the explicit tasks. However, it should be noted that dyslexia was not established in Sperling et al.'s participants, and the reading deficit in these participants may therefore be due to general poor learning abilities.

Vicari et al. (2005) found further evidence supporting the hypothesis that not only implicit sensory motor learning is affected in dyslexia, but also implicit learning in other domains. The authors found that children with DD are impaired both on SRTT performance and on mirror drawing performance. In addition to implicit sensorimotor learning, implicit artificial language learning has also been found to be impaired in dyslexic children (Pavlidou, Kelly & Williams, 2010).

In contrast, there is also evidence that dyslexics do not have a deficit in implicit learning. Kelly, Griffiths and Frith (2002) found both spatial sequence learning (without motor responses) and non-spatial motor sequence learning to be intact in dyslexics. Also, Rüsseler, Gerth and Münte (2006) found no impairments of implicit sensorimotor learning nor implicit artificial grammar learning. Finally, Waber et al. (2003) did not find a clear effect of reading skill, cognitive ability and attention on SRTT performance in a large sample of children without neurological problems. Details of the sequences used in the SRTT's and grammars used in AGL task as well as sampling may be part of the cause for the diverging results. Participant age may also be an important factor. For example, Rüsseler et al. tested adults on a visual artificial grammar learning and found no implicit learning deficit in dyslexics, Pavlidou et al. (2010) on the other hand tested children using a similar paradigm but did find impaired implicit learning in dyslexics. Rüsseler's adult participants may have compensated for their poor implicit learning skills.

Neuroimaging research has shown that dyslexics have different patterns of brain activation during implicit learning. The neural network thought to be involved in implicit learning includes parts of the inferior frontal cortex, the basal ganglia and the cerebellum[1] (Doyon, Penhune & Ungerleider, 2003; Dominey, 2005; Ullman, 2004; Lieberman, Chang, Chiao, Bookheimer & Knowlton, 2004). Menghini, Hagberg, Caltagirone, Petrosini and Vicari (2006) performed an fMRI study in which participants were asked to perform an SRTT inside the scanner. A higher cerebellar and parietal activation was found in the DD group than in the control group especially in the later phases of the experiment. Additionally, the SRTT revealed a behavioral implicit learning impairment in the dyslexic group (no significant difference between reaction times in last sequence block compared the last random block). Nicolson et al. (1999) conversely, found lower right cerebellar hemisphere activation during sensorimotor learning and execution of a prelearned motor sequence using PET. In the latter study, the stimuli of the motor sequence were presented auditorily instead of visually.

In addition to these functional neuroimaging studies, structural and biochemical studies on brain abnormalities in dyslexia have also been performed. For example, Rae et al. (1998) found biochemical differences in dyslexics and not in controls between the left and right cerebellar hemisphere

[1] In two fMRI studies investigating brain activation in artificial grammar learning the cerebellum was not found to be involved (Lieberman, Chang, Chiao, Bookheimer & Knowlton, 2004; Skosnik et al., 2002). But, in both studies scanning took place during the test phase and not during the learning phase. Thus, the results may reflect neural correlates of implicit memory instead of neural correlates of implicit learning.

and the left and right temporo-parietal lobes. Also, Brambati et al. (2004) found focal reductions in cerebellar gray matter in developmental dyslexics.

The studies discussed above show that evidence of implicit learning being impaired in dyslexics has not been conclusive. Also, even though many studies have shown impaired (sensori)motor sequence learning in developmental dyslexics, it is less clear whether implicit language learning is equally impaired. If implicit motor and language learning are affected to the same degree in dyslexic participants, this would support the hypothesis that implicit language and sensorimotor learning are instances of the same domain general implicit skill acquisition mechanism, and that this mechanism is deficient in dyslexia. Wijnen (2013) suggested the inferior frontal lobe – basal ganglia - cerebellar network subserves not only implicit sensorimotor learning, but also implicit language learning.

The aim of the present study is to test the hypothesis that both implicit language learning and implicit learning in the motor domain are impaired in dyslexia, while explicit (declarative) learning remains unaffected. A group of adults with DD and a control group performed a task involving implicit language learning (artificial grammar learning), a task involving implicit sensorimotor learning (implicit serial reaction time task) and a task involving explicit sensorimotor learning (explicit serial reaction time task). It is predicted that a) the controls perform better than the dyslexics at both implicit sensorimotor learning and implicit language learning, b) dyslexics and controls perform equally well on the explicit sensorimotor learning task, and c) as implicit language and sensorimotor learning are thought to be instances of the same domain general skill ‘implicit learning’, performance on the implicit language and sensorimotor learning tasks are predicted to be correlated.

2 Methods

1.1 Participants

54 participants took part in this experiment. Of these, 27 were diagnosed with developmental dyslexia (11 male, 16 female). The other 27 participants constituted a control group consisting of age-matched participants without

developmental dyslexia or other neuropsychological disorders (8 male, 19 female). Participants were recruited via the Utrecht Institute of Linguistics OTS participant database, and through an online participant database ("proefbunny", 2012). The average age of the participants was 23,8 (SD=5.53). All participants were native speakers of Dutch.

1.2 Design and procedure

Participants came to the lab for three sessions: a neuropsychological test session, an MRI scan and a behavioral test session. The focus of this paper is on the data gathered in the behavioral test session. The other two sessions will be described very briefly below.

First, participants were asked to partake in a neuropsychological test session. The test battery of this session consisted of 12 tests assessing IQ, spelling, motor performance, verbal fluency, executive function, phonological awareness, attention and time discrimination ability (see appendix 1 for a complete overview of the tests used). The session took approximately 90 minutes. In this session it was determined whether a participant met our criteria for dyslexia, and whether they were suitable for MRI scanning in the second session. Participants were considered to be dyslexic when 1) scores on both the one-minute-test[2] and the Klepel[3] were below the 20th percentile, 2) when either the one-minute-test or the Klepel score were below the 10th percentile, or 3) when the discrepancy between the participant's score on the one-minute-test and on the verbal competence test[4] was more than or equal to 60%.

The neuropsychological test battery also allowed us to control for possible confounds in the behavioral part of the experiment. Most importantly for this paper, we consider the relation between sustained attention (Bourdon-Wiersma Vigilance test) and our implicit learning measures.

In the second session an MRI scan was made. The volumes of the left and right cerebellar grey and white matter as well as the total brain volume were

[2] In the one-minute-test the participant had to read as many nonsense words out loud as possible in one minute. The number of words the participant read correctly was measured.

[3] In the Klepel the participant had to read as many nonsense words as possible within two minutes. The number of words the participant read correctly was measured.

[4] In the verbal competence test the participant was given 20 word pairs (e.g. 'poem' and 'statue'). For each word pair the participant was asked to describe in which way the words were similar. The answers were scored as correct (2), partially correct/incomplete (1) or incorrect (0).

measured using the MRI data, and these volumes will be related to participants' performance on the behavioral tasks in the third session. The results of this part of the project are beyond the scope of this paper. Seven participants were not suitable for MRI scanning but were still asked to come back for the final test session.

The final test session consisted of an implicit sensorimotor learning task (implicit serial reaction time task), an explicit sensorimotor learning task (explicit serial reaction time task), and an implicit artificial grammar learning (AGL) task (Reber, 1967). The order of the implicit serial reaction time task (ISRTT) and AGL was counterbalanced between participants (Table 1). The explicit serial reaction time task (ESRTT) was always performed last in order to prevent the participants adopting explicit learning strategies in subsequent implicit tasks. The total session took approximately 45 minutes. All tasks were performed using a computer in a sound proof booth. The three tasks and the stimuli will be described in more detail below.

Due to a technical error in the script of the AGL task, the responses of 34 participants were not recorded (17 dyslexics and 17 controls). The participants whose responses were lost were asked to partake in another AGL task. When the error was discovered and fixed, the sequences of nonwords for the AGL task learning phase and test phase stimuli were changed in order to minimize possible practice effects in the retest group. Both the retested group and the 20 other participants (10 dyslexics and 10 controls) were exposed to the same sequences of nonwords in the learning phase and in the test phase of the task. Post-hoc analysis revealed that there was no significant difference between the AGL performance of the retested group and the group only tested once[5], indicating that there was no detectable practice effect. The interval between test and retest was kept as constant as possible (M=22.21, SD=3.91, range=16 to 32).

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[5] Differences in performance between the retested group and the group tested only once were explored with a factorial ANOVA with d' (please refer to section 3.1 for a description of d') as the dependent factor and group (dyslexic, control) and test repetition (retested, tested once) as independent factors. No significant main effect of test repetition was found (F (1,48)=.15, p=.70), nor was there a significant interaction between test repetition and group (F(1,48)=.22, p=.64). This indicates that there was no detectable practice effect found in the retest group (M=.17, SD=.39) as compared to the performance of the group tested only once (M=.22, SD=.51). Furthermore, the retested controls (M=.25, SD=.57) did not perform better than controls tested once (M=.26, SD=.38), and the retested dyslexics (M=.19, SD=.46) did not perform better than the dyslexics tested once (M=.07, SD=.39).

Participants received a reimbursement of 10 euros for each of the sessions, including the retest session.

1.3 Behavioral tasks

All behavioral tasks were programmed using zep 0.18 (Veenker, 2012).

1.3.1 Artificial grammar learning task

An auditory artificial grammar learning task was used in this study to assess implicit language learning skills in dyslexics and controls. The task consisted of three phases: a lexical recognition phase, a learning phase and a test phase. The lexical recognition phase was designed to make sure that participants would correctly perceive the nonwords they would subsequently be exposed to in the learning phase. Participants read a list with the eight nonwords that would appear in the task out loud once. Then, they were exposed to each of these nonwords in random order through headphones, and they were asked to type each nonword directly after exposure. When they pressed Enter after typing the word, feedback ('correct', or 'incorrect') appeared on the screen. A nonword was repeated when the entry was incorrect. There were 4 versions of each nonword with different prosodic features. Each version of a nonword corresponded with a position in a sequence of four participants would subsequently be exposed to in the learning phase of the AGL task. The prosodic characteristics of each nonword position in the sequence were based on the prosody of natural center-embedded sentences (see appendix 2). Participants were exposed to each version of the nonwords in the lexical recognition phase. The phase ended only after participants reached perfect performance on all 4 versions of the 8 words.

In the learning phase participants were exposed to a stream of 48 sequences of four spoken nonwords repeated 8 times in shuffled order. All 48 sequences made up phrases that were part of an artificial language. The grammar of the artificial language was the same as the grammar used by Mueller, Bahlmann & Friederici (2010) and is described in appendix 2, as are the stimuli. In order to avoid that participants would start to pay explicit attention to the sequences of nonwords they were exposed to, they were distracted with a task. The participants were instructed to color four fairly simple mandalas. Their instructions were to color in as many of the four mandalas they could, using all the available colors.

Before starting the subsequent test phase participants were told that they had listened to a science fiction language. Then, they were exposed to 48 artificial language phrases consisting of sequences of four nonwords. Half of the phrases were consistent with the grammar of the artificial language the participants were exposed to in the learning phase, and the other half was not. The participants were asked to press 'Yes' on a two button box when they thought the string belonged to the language they were exposed to in the learning phase, and 'No' when they thought the string did not belong to that artificial language. No feedback was given during the test phase. Covertly, the test phase was divided in two parts of 24 sequences each. For half the participants (12 dyslexics and 13 controls), the first 24 sequences consisted of 25% grammatical and 75% ungrammatical strings, whilst the last 24 sequences consisted of 75% grammatical and 25% ungrammatical strings (distribution 1). For the other half of the participants (13 dyslexics and 14 controls) test sequences were distributed in the opposite order (distribution 2). The two distributions allowed us to control for possible learning effects during the test phase. It was expected that if participants learned during the test phase, participants exposed to sequences with distribution 2 (75% grammatical sequences in the first half of the test phase) would perform better than participants with distribution 1 (25% grammatical sequences in the first half of the test phase).

At the end of the test phase, participants were asked to rate on a 7 point scale ranging from 'volstrekt onzeker' (absolutely uncertain) to 'volstrekt zeker' (absolutely certain) how confident they were about the answers they had given in the test phase. Also, a verbal report score was assigned to participants based on the participants' responses to a number of questions asked after the test phase. The questions asked were designed to find out how much explicit knowledge a participant had gained of the artificial grammar they had been exposed to. The questions started out more general and became more specific: e.g. How did it go? Did you find it easy or hard? Did you have any idea about when to answer 'yes' or 'no'? Did you base your answers on your intuitions? Did you have a strategy? If so, what was it? Participants were assigned a verbal report score of 0 when their answers revealed they had noticed no rule of the artificial language they were exposed to (see appendix 2), a score of 1 when they had found the category rule, a score of 2 when they had found the dependency rule, a score of 3 when they had found both rules, and a score of 4 when they had found some other rule (e.g. 'I always pressed yes when dres was the final word').

1.3.2 Implicit serial reaction time task

To assess implicit sensorimotor skill learning in dyslexics and controls an implicit serial reaction time task was used in which participants were assigned either of two fixed sequences existing of 12 elements (sequence 1: 1,3,1,2,4,1,2,3,4,2,3,4, or sequence 2: 2,4,3,1,3,2,4,2,1,3,1,4). The participants that were assigned sequence 1 in the ISRTT were assigned sequence 2 in the explicit serial reaction time task (see below) and vice versa.

The task consisted of a learning phase and a generation phase. Participants seated in front of a computer screen with a four button box at hand. In the learning phase, four frames were presented on the screen in front of the participant (Figure 1). Each of these frames corresponded to a button on the button box. During this phase, the frames on the screen lit up one after the other, and participants were instructed to press the corresponding button each time a frame lit up as quickly and accurately as possible. The participants controlled the upper left and right buttons with their middle fingers and the lower left and right buttons with their index fingers.

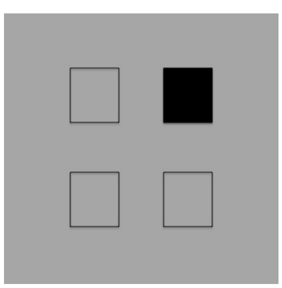

Figure 1 SRT screen with right top frame lighting up

The learning phase was divided in seven blocks. The participants were not made aware of this structure. Only a fixation cross at the beginning of each block could give the participant a hint of this structure. In the first (R1) and the sixth block

(R6), the order in which the frames lit up was random. In all other blocks (S2-S5 and S7) the same 12 element sequence (sequence 1 or sequence 2) was repeated six times.

In the subsequent generation phase participants were first asked whether they had noticed anything about the task. If they had not noticed the fixed repeating sequence they were told there was one. They were then asked to try to reproduce the fixed sequence they had been exposed to. Participants received a piece of paper and a pen they could use in case they wanted to think about the sequence they would subsequently enter using the button box. The participants were given three attempts to reproduce the sequence. All 12 elements (12 button presses) had to be entered before they could continue. After each attempt participants gave a confidence rating on a 7 point scale ranging from ‘volstrekt onzeker’ (absolutely uncertain) to ‘volstrekt zeker’ (absolutely certain).

1.3.3 Explicit serial reaction time task

An explicit version of the serial reaction time task was used to test whether controls and dyslexics would perform equally well on a task assessing explicit learning. The design of the ESRT task was the same as the design of the ISRT task. Two changes were made to the learning phase in order to make the learning that occurred in this task explicit. First, participants were told beforehand that there would be blocks with random sequences and blocks with a fixed sequence. They were asked to determine and remember the fixed sequence. Secondly, participants were asked to determine for each block at the end of the block whether the sequence they were exposed to was random or fixed, and also to indicate how certain they were of their answer on a 7 point scale ranging from ‘volstrekt onzeker’ (absolutely uncertain) to ‘volstrekt onzeker’ (absolutely uncertain). The analysis of the participant’s responses to the question whether the sequences in the blocks were fixed or random is beyond the scope of this paper.

Group	Task order		
A	$AGL_{distribution\ 1}$	$ISRTT_{sequence\ 1}$	$ESRTT_{sequence\ 2}$
B	$ISRTT_{sequence\ 1}$	$AGL_{distribution\ 1}$	$ESRTT_{sequence\ 2}$
C	$AGL_{distribution\ 2}$	$ISRTT_{sequence\ 2}$	$ESRTT_{sequence\ 1}$
D	$ISRTT_{sequence\ 2}$	$AGL_{distribution\ 2}$	$ESRTT_{sequence\ 1}$

Table 1 Overview of the 4 possible orders of task and SRT task sequence

3 Results

3.1 Artificial grammar learning task

In this section, we will first address the question whether the artificial grammar participants were exposed to was learned by each group (dyslexics and controls). The performance in the two groups will be compared and related to BWVT score (a measure sustained attention capacity). Furthermore, we will assess how much explicit knowledge of the rules of the artificial grammar participants have gained. Finally, we will test whether there was an effect of task order on AGL performance.

Signal detection theory was used to analyze the data collected in the AGL task, Participants answered 'Yes' or 'No' 48 times to the question whether the stimulus they heard belonged to the artificial grammar or not. Signal detection theory provides a measure (d') for the sensitivity to detect a signal. This measure is not affected by the presence of a response bias.

D' represents the difference between the z-scores of the probability of a hit and the probability of a false alarm in a participant's responses:

$$d' = z(Phit)-z(Pfa)$$

In this experiment, the cases in which participants answered 'yes' and the presented stimulus was grammatical were coded as hits, whereas the cases in which participants answered 'yes' but the presented stimulus was ungrammatical were taken to be false alarms. D' increased as the sensitivity to grammatical items increased. A d' value close to zero represents chance performance (MacMillan & Creelman, 2005). A positive d' value significantly different from zero represents above chance sensitivity to grammatical items. A negative d' significantly different from zero would mean an above chance sensitivity for identifying non-grammatical items as grammatical.

By means of a one sample t-test it was tested whether d' in each group (dyslexic and control) was significantly different from chance. The control group in the present experiment performed above chance; the d' of this group was significantly greater than zero (M= .26, SE=.096), t(26)=2.67, p=.01, r=.46. The dyslexics on the other hand did not perform above chance. The d' of the dyslexics was not significantly different from zero (M=.14, SE=.085, t(24)=1.67, p=.11). The difference between the performance of the dyslexic group and the control group did not reach significance (t(50)=.89, p=.38, r= .12).

Interestingly, a significant correlation was found between d' and the Bourdon-Wiersma Vigilance test (BWVT, a test of sustained attention, see appendix 1 for a description) score for the dyslexics (r=.45, p=.024) but not for the controls (r=.23, p=.24)[6]. A log transformed measure of the BWVT was used because the assumption of normality was violated in the non-transformed data (D(54)=.14, p=0,02). Also, dyslexics (M=1.78, SD=.06) performed significantly worse on the Bourdon-Wiersma Vigilance Test than controls (M=1.81, SD=.06), t(52)=2.22, p=0.03.

3.1.1 Awareness of the rules of the artificial grammar

Two measures of awareness of the knowledge gained in the AGL were taken after the test phase of the AGL: a verbal report score based on how much and what type of explicit knowledge was gained, and a confidence rating (participants answered the question how confident they were about their answers on a scale from 1 to 7). Only one participant had a verbal report score of 1, indicating that she had discovered the category rule of the artificial grammar

[6] Since a significant difference between performance of dyslexics and controls on the Bourdon-Wiersma Vigilance test was found, the BWV test score could not be used as a covariate in our analysis of the AGL task data as that would constitute a violation of an ANCOVA assumption.

(see Appendix 2). Fourteen participants reported an erroneous rule (verbal report score 4). The other participants discovered no rules (see Table 2).

If the knowledge gained of the grammar was implicit, verbal report score (indicating degree and type of explicit knowledge of the grammar) should not be associated with d'. Also, confidence rating should not be correlated to d' as that would indicate participants being aware of how well they performed, indicating that the knowledge they gained may not be implicit.

To assess whether verbal report score and confidence rating were related to our implicit learning measure (d'), a two-way ANOVA was conducted with d' as the dependent variable and verbal report score and confidence rating as the independent variables. There was no significant main effect of verbal report score ($F(2,40)=.49$, $p=.62$), indicating verbal report score was not associated with performance. A non-significant main effect of confidence rating was found ($F(5,40)=.19$, $p=.97$), indicating that performance on the AGL task was not associated with how confident participants were about their responses. Table 4 shows the frequencies with which each confidence rating was given. Finally, there was no significant interaction between confidence rating and verbal report score ($F(4,40)=.71$, $p=.59$).

Confidence rating	N
1: volstrekt onzeker (absolutely uncertain)	5
2: redelijk onzeker (reasonably uncertain)	12
3: enigszins onzeker (somewhat uncertain)	10
4: neutraal(neutral)	7
5: enigszins zeker(somewhat certain)	17
6: redelijk zeker (reasonably certain)	1
7: volstrekt zeker (absolutely certain)	0

Table 2 Frequencies of confidence ratings given

3.1.2 Effects of condition

The question whether there were effects of task order (AGL-ISRTT vs. ISRTT-AGL) and AGL test sequence distribution (see Table 1) was explored by means of a factorial ANOVA with d' as the dependent variable and task order and AGL test sequence distribution as independent variables. The task order was coded taking into account whether a participant was retested on the AGL task. Retested participants were all coded as having performed the AGL task after the ISRTT. No significant main effect of task order was found (F(1,48)=.49, p=.49).

The main effect of AGL test sequence distribution did not reach significance either (F(1,48)=.34, p=.56). The performance of the group exposed to primarily grammatical sequences in the first half of the test phase and primarily ungrammatical sequences in the second half of the test phase was not different from the performance of the group with the opposite distribution of grammatical and ungrammatical sequences. This result shows that no significant learning occurred during the test phase. The interaction between AGL task sequence distribution and task order did not reach significance ((F1,48)=.06, p=.81).

3.1.3 Summary of AGL results

Even though the control group performed significantly above chance on the AGL task and the dyslexics did not, the difference between the performance of controls and dyslexics did not reach significance. BWVT score (sustained attention) was significantly correlated with our performance measure d' in the dyslexic group but not in the control group. Furthermore, no significant correlation between confidence rating or verbal report score and d' was found.

3.2 Implicit serial reaction time task

The first question addressed in this section is whether learning of the sequence occurred in the Implicit Serial Reaction Time Task in each group. To this end, reaction times will be compared across blocks. We will then proceed to compare two measures of learning (described below) across groups. Furthermore, we will test whether our measures of implicit learning can be dissociated from how aware participants were of the sequence they were exposed to. Finally, it will be assessed whether there were effects of task order and of the sequence (sequence 1 or sequence 2) participants were exposed to.

Figure 2 shows the mean reaction time in each block for each group. Both groups show a typical learning trend. For the controls a gradual decrease in reaction time can be seen from block R1 to block S3. An increase in reaction time can be seen for block R6, the first random block after four fixed sequence blocks.

Reaction times in block S7, the last fixed sequence block, were shorter as compared to block R6. As for the dyslexics, an unexpected slight increase in reaction time can be seen from block R1 to block S2, followed by a gradual decrease from block S2 to block S4. As for the control group, an increase in reaction times can be seen from block S5 to block R6, followed by a decrease from block R6 to block S7. Reaction times of the dyslexics are longer than reaction times of the controls in each block. In appendix 3 the individual data (median reaction time in each block for each participant) is shown.

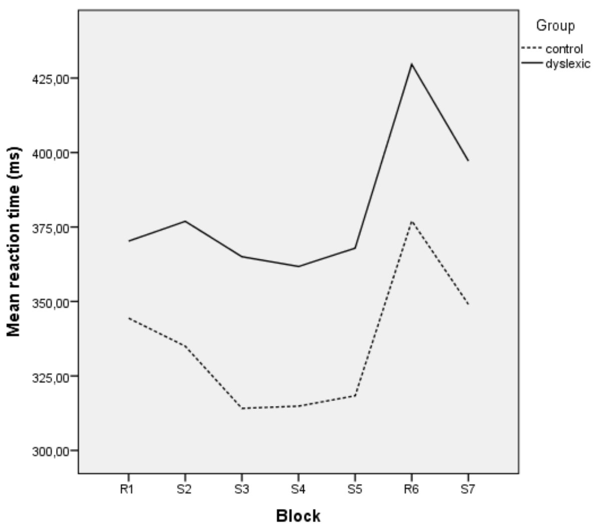

Figure 2 Mean reaction times per block for each group in the ISRTT

To assess whether reaction times differed over blocks a mixed ANOVA was conducted with median reaction time (aggregated per participant) as dependendent variable, block as the within participants variable and group as the between participants variable[7]. The assumption of within group normality was violated. The violation of normality, however, was not expected to affect the F value considerably as we have more than 50 (54 aggregated) observations (see Stevens, 1996, p. 243). Also, Gelman and Hill (2007, p.46) do not recommend the diagnostics of normality in regression, and ANOVA is a special case of regression

7 Aggregated (median) reaction times were used in the analysis of the implicit SRT task as well as the explicit SRT task because of time limitations. Using aggregated data here is not ideal since a lot of variance in our dataset is lost in this analysis. The problems caused by using aggregated data that violate assumptions of normality and homogeneity of variance can be alleviated by reanalyzing the dataset with hierarchical models using the non-aggregated data.

(Field, 2009, p. 349). Therefore, in the rest of this paper, violations of the assumption of normality will not be reported unless a transformation of the data improved normality considerably or a suitable nonparametric test was available.

Greenhouse-Geisser correction was used because the assumption of sphericity was violated. A significant main effect of block was found ($F(3.24,168.61)=29.79$, $p=.000$). Also, there was a significant main effect of the between participants factor group ($F(1,52)=5.88$, $p=.019$). The mean reaction times of the controls in each block were shorter than of the dyslexics. It should be noted that the assumption of homogeneity of variance was violated in three of the seven levels of the repeated measures variable block (block 1: $F(1,52)=5.29$, $p=.0.25$, block 2: $F(1,52)=4.29$, $p=.43$, block 4: $F(1,52)=5.00$, $p=.030$) and we should be cautious interpreting this effect. However, since group sizes were equal, F is thought to be robust (Stevens, 1996, p. 249). No significant interaction between block and group was found ($F(3.24,168.61)=1.15$, $p=.33$).

Two between block comparisons are most important for this analysis as the differences between these blocks will be used as a measure of implicit learning that occurred in the task. First of all, a post-hoc bonferroni pairwise comparison was performed between block S2 (the first sequence block) and block S4 (the block with the shortest grand mean reaction time, $M=338.31$, $SD=78.74$). Reaction times were shorter in block S4 ($M=338.31$, $SD=78.74$) than in block S2 ($M= 355.94$, $SD=70.98$), and this difference is significant ($p=.004$), indicating participants became faster over the first three sequence blocks. Secondly, there was a significant difference between reaction times in block R6 ($M=403.33$, $SD=77.19$) and block 5 ($M=343.13$, $SD=85.07$) ($p=.000$), indicating that changing from a sequence to a random block after four sequence blocks influenced participant's speed.

3.2.1 Learning effects

Two learning measures were formulated to assess the degree of implicit learning that occurred in our two experimental groups. First, a learning variable was calculated by subtracting participants' median reaction times in block S2 (the first fixed sequence block) from their median reaction times in block S4. From here on this measure will be referred to as S2-S4. Block S4 was chosen for this measure and not the last sequence block (S5) before the second random block (R6) because in S4 the grand mean of the median reaction times was the shortest (M=338.31, SD=78.74).

Besides representing a learning effect, a decrease in reaction times from block S2 to block S4 may also indicate a general effect of gaining experience with the task instead of actually learning the sequence. A second variable was computed by subtracting median reaction times in block R6 from those in block S5. This variable will be referred to as R6-S5. Longer reaction times in block R6 as compared to block S5 are expected to be caused by the participant switching from the (partially) learned repeating sequence of button presses to random button presses. A disadvantage of this last measure is that a participant's executive function may influence the measure as it involved switching from one type of task to the next (pressing buttons in a fixed sequence to pressing buttons in random order).

The S2-S4 variable was not normally distributed for the dyslexic group (D(27)=.17, p=.040). Therefore, to assess the difference between the amount of learning that occurred in the dyslexic group and the control group a Mann-Whitney test was performed with S2-S4 as the dependent variable and group as independent variable. The mean reaction time of the dyslexics and of the controls were shorter in block S4 as compared to block S2. The difference in the S2-S4 learning effect of the dyslexics (Mdn=16.50) and the control group (Mdn=25.00) did not reach significance (U=291, z=-1.27, p=.21, r=-.17).

The difference between the dyslexics and controls on R6-S5 were assessed using an independent samples t-test. The mean reaction times were higher in block 6 than in block 5 in both groups. There was no significant difference in R6-S5 between dyslexics (M=61.70, SE=7.23) and controls (M= 58.70, SE=10.36), t(52)=-.24, p=.81, r=0.03. The two learning measures S2-S4 and R6-S5 were not significantly correlated (r=.22, p=.11).

To assess the relation between attention and the two learning effects it was tested whether these measures correlated. No correlation was found between the log transformed Bourdon-Wiersma Vigilance test score and S2-S4 (r=.16, p=.24) or R6-S5 (r=.13, p=.34). Also when the data was split by group there was no significant correlation between S2-S4 or R6-S5 and BWVT for dyslexics (S2-

S4: r=.10, p=.63, R6-S5: r=.24, p=.23) or controls (S2-S4:r=.21, p=.30, R6-S5: r=.09, p=.66).

3.2.2 Generation phase

To be able to test whether the learning that occurred in the ISRTT was implicit, two measures of awareness were collected. First of all, in the generation phase participants had three attempts to try to reproduce the sequence they had been exposed to in the learning phase. The length of the longest correct chunk that was present in all three attempts was taken to be the main measure of explicit knowledge ('longest correct overlap'). Furthermore, after each attempt participants were asked to give a confidence rating on a scale ranging from 1 to 7. The mean of these ratings was used as an extra indication of awareness of the knowledge reflected by the longest correct overlap.

The length of the correct chunk produced in each of a participant's three attempts to reproduce the sequence does not differ significantly between dyslexics (M=3.04, SD=2.66) and controls (M=3.33, SD=1.19) t(52)=.53, p=.60.

The mean confidence ratings of the three given after each attempt to reproduce the sequence were also not significantly different for controls (M=2.35, SD=1.45) and dyslexics (M=2.67, SD=1.54), t(52)=-.79, p=.44.

If our learning measures (S2-S4 and R6-S5) mainly reflected implicit learning, longest correct overlap should not be correlated to our learning measures. However, the mean confidence rating should be correlated with the longest correct overlap.

There was no significant correlation between longest correct overlap and S2-S4 (r=-.006, p=.97) or R6-S5 (r=.23, p=.10) indicating that the amount of explicit knowledge gained in the task was not associated with the amount of implicit learning that occurred. Mean confidence rating however, was significantly correlated to both S2-S4 (r=.27, p=.049) and R6-S5 (r=.28, p=.038). It is unclear what these correlations mean, as the confidence rating was based on how confident participants were about their three attempts to reproduce the sequence in the generation phase. As expected, longest correct overlap was also significantly correlated to mean confidence rating (r=.38, p=.004).

No significant correlation between the Bourdon-Wiersma Vigilance test score and longest correct overlap was found for the controls (r=-.15, p=.44) nor for the dyslexics (r=-.14, p=.48).

3.2.3 Effects of condition

To assess the effect of task order and sequence order on the learning effects a factorial ANOVA with task order (AGL-ISRTT or ISRTT-AGL) and ISRTT sequence (sequence 1 or sequence 2) as independent variables and S2-S4 as dependent variable was performed to check whether these factors influence ISRTT performance. Retested participants were coded as having test order ISRTT-AGL.

No significant main effect of task order was found (F(1,50)=.03, p=.87). This indicates that having performed an AGL task before an ISRT task did not influence performance on the ISRTT and vice versa. A significant main effect of sequence was found (F(1,50)=4.11, p=0,048). The learning effect S2-S4 (the difference between the median reaction times of block 2 and the median reaction times in block 4) was larger for sequence 2 (2 4 3 1 3 2 4 2 1 3 1 4) (M=26.52, SD=31.91) than for sequence 1 (1 3 1 2 4 1 2 3 4 2 3 4) (M=8.76, SD=30.13). No significant interaction between task order and ISRTT sequence is found (F(1,50)=.49, p=.49).

To test whether the difference between the learning effect S2-S4 for sequence 1 and sequence 2 was the same for each group, an ANOVA was performed with S2-S4 as dependent variable and group and sequence as independent variables. The main effect of sequence was significant (F(1,50)=4.19, p=.046). The main effect of group was not significant (F(1,50)=.25, p=.62), nor was the interaction between group and sequence (F(1,50)=.05, p=.82).

A similar factorial ANOVA was performed with learning effect R6-S5 as dependent measure and task order and ISRTT sequence as independent measures. The assumption of homogeneity of error variances (F(3,50)=2.84, p=.047) was violated. But as noted before, group sizes were equal and therefore F was expected to be robust (Stevens, 1996, p. 249). Again, there was no significant main effect of task order (F(1,50)=.54, p=.47), nor a main effect of ISRTT sequence (F(1,50)=1.87, p=.18) or an interaction between task order and ISRTT sequence (F(1,50)=.45 p=.50). This result indicates that having performed an AGL task before an ILSRT task does not influence performance on the ISRTT and vice versa.

Even though a difference in S2-S4 between the two sequences was found, this effect is not expected to influence our overall result as no interaction between group and sequence was found, the two sequences were fairly equally distributed within the groups (sequence 1: 14 dyslexics and 13 controls, sequence 2: 13 dyslexics and 14 controls) and no effect of sequence was found on our other learning measure R6-S5.

3.2.4 Summary of ISRTT results

Significant main effects of block and group on reaction time were found. Dyslexics were slower in their responses than controls, but no significant interaction between block and group was found. Post-hoc tests revealed significant differences between block S2 and block S4, and between block S5 and R6. Reaction times decreased from block S2 to block S4 and increased from block S5 to block R6, indicating that participants learned the sequences.

No significant difference was found between the two groups on our implicit learning measures (S2-S4 and S5-R6). Attention (Bourdon-Wiersma Vigilance Test score) was not significantly correlated to our learning measures for controls or dyslexics.

No significant between group effect was found on our explicit knowledge measure 'longest correct overlap'. Longest correct overlap was not significantly correlated with S2-S4 or R6-S5. Longest correct overlap was significantly correlated to mean confidence rating. BWVT score was not significantly correlated to longest correct chunk.

A significant main effect of sequence was found on the S2-S4 learning measure, but no interaction between group and sequence was found. No significant main effect of sequence was found on the R6-S5 learning measure.

3.3 Analysis of correlations between AGL and ISRTT performance

To assess whether Artificial Grammar Learning (implicit language learning) and sequence learning in the Implicit Serial Reaction Time Task (implicit sensorimotor learning) tap in to an underlying domain general learning mechanism it was tested whether our learning measure in the AGL task (d') was correlated with either of the two learning measures of the ISRTT. No significant correlation was found between d' and S2-S4 ($r=.044$, $p=.76$) or R6-S5 ($r=.048$, $p=.74$). Also, when we split the data by group, no significant correlations were found between d' and S2-S4 or R6-S5 for the dyslexics (S2-S4: $r=.02$, $p=.94$, R6-S5: $r=.02$, $p=.91$) or for the controls (S2-S4: $r=.05$, $p=.81$, R6-S5: $r=.07$, $p=.74$).

3.4 Explicit serial reaction time task

Like for the implicit SRTT, the first question addressed in this section is whether learning of the sequence occurred in the explicit Serial Reaction Time Task in each group. To this end, reaction times will be compared across blocks. We will then proceed to compare two measures of explicit sensorimotor learning across groups. Furthermore, we will test whether our measures of explicit learning are correlated with our measure of explicit knowledge (longest chunk correct). Finally, we will test whether there was an effect of the sequence participants were exposed to on performance.

Figure 3 shows the mean reaction times in each block for each group. Whereas the control group shows a clear learning pattern with reaction times gradually decreasing from block R1 to block S5, strongly increasing in block R6 and decreasing again in block 7, the dyslexic group shows a very different pattern. The reaction times of the dyslexics decrease only slightly from the first sequence block S2 to the last sequence block S7, but no strong increase in reaction times is seen in block R6. Individual data (median reaction time in each block per participant) is shown in appendix 4.

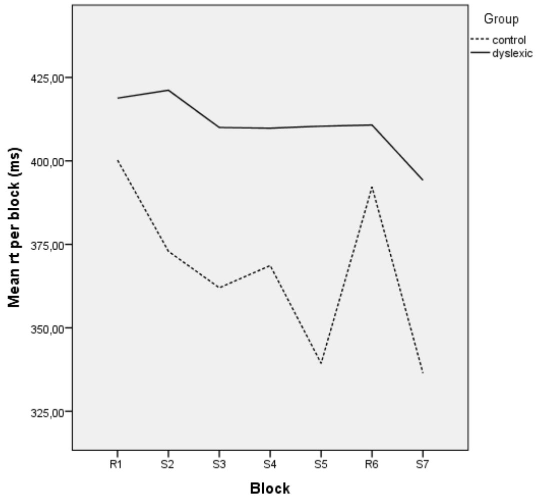

Figure 3 Mean reaction times per block for each group in the ESRTT

We start out our analysis of the ESRTT with a mixed design ANOVA with the median reaction time as dependent variable, block as repeated measures factor and group as between participants factor. A significant main effect of block was found (F(3.36, 174.55)=2.84, p=.034). The main effect of group was not significant (F(1,52)=2.21, p=.14), nor was the interaction between group and block (F(3.36, 174.55)=1.13, p=.34).

As Figure 3 shows such a strikingly different pattern for dyslexics than for controls we further explored the data by testing whether a significant effect of block could be found within each group by means of a separate repeated measures ANOVA for each group. In the control group a significant effect of block was found (F(3.29,85.46)=4.74, p=0.002), whereas no such effect was found in the dyslexic group (F(2.20, 57,10)=.36, p=.72).

Furthermore, post hoc paired samples t-test were performed to compare reaction times in block S2 and block S5 and between block R6 and block S5. We were interested in the difference between block S2 and S5 because reaction times were shortest in block S5 (M=374.88, SD=169.49) and we will therefore use the difference between S2 and S5 as a measure of learning (see below). The post hoc paired samples t-tests revealed that the difference in median reaction times between block S2 and block S5 was significant in the control group (t(26)=2.92, p=.007) but not in the dyslexic group (t(26)=.35, p=.73). The same contrast was found for the difference in median reaction times in block S5 and

R6. A significant difference was found for the control group (t(26)=-5.18, p=.000), but not for the dyslexic group (t(26)=-.01, p=.99).

3.4.1 Learning effects

The measures used to assess learning in this task are S2-S5 (median reaction times in block S2 minus median reaction times in block S5), and R6-S5 (median reaction times in block R6 minus median reaction times in block S5).

An independent samples t-test revealed that the learning effect S2-S5 of the dyslexics (M=10.78, SD=160.00) is not significantly different from the S2-S5 learning effect of the controls (M=33.56, SD=59.73), t(52)=.69, p=.49.

Also, the learning effect R6-S5 of the dyslexics (M=.37, SD=183.36) is not significantly different from the learning effect R6-S5 of the controls (M=52.83, SD=52.95), t(52)=1.43, p=.16. The large standard deviations here may be the reason why no significant between group differences are found even though the graph in Figure 3 shows such a remarkably different patterns for dyslexics and controls.

S2-S5 was not significantly correlated to the log transformed measure of the Bourdon-Wiersma Vigilance test of attention (r=-.001, p=.99), nor was R6-S5 (r=.11, p=.43). When the data is split by group however, a significant correlation is found between R6-S5 and BWVT for the controls (r=.48, p=.012) but not for the dyslexics (r=-.05, p=.80).

3.4.2 Generation phase

Like for the ISRTT, a t-test was performed to test whether the length of the correct chunk produced in each of a participant's three attempts to reproduce the sequence differed between groups. No significant difference between dyslexics (M=4.30, SD=2.33) and controls (M=5.37, SD=3.55) was found (t(44.91)=1.31, p=.20), indicating that the groups were aware of the sequence to a similar degree.

The mean of the confidence ratings given in response to each attempt to reproduce the sequence did not differ significantly between controls (M=3.75, SD=1.70) and dyslexics (M=3.51, SD=1.51), t(52)=.56, p=.58).

Mean confidence rating and longest correct overlap were highly correlated (r=.68, p=.000), indicating that participants were generally able to accurately estimate how much of the sequence they had managed to learn. Longest correct overlap was not significantly correlated to S2-S5 (r=.12, p=.38) or to R6-S5 (r=.10, p=.48). Also, mean confidence rating was not significantly correlated with S2-S5 (r=.03, p=.84), or R6-S5 (r=.07, p=.62).

BWVT score was not significantly related to longest correct overlap for dyslexics (r=.09, p=.65) or controls (r=.14, p=.50).

3.4.3 Effects of condition

To test whether there was an effect of sequence (sequence 1 or sequence 2) on the performance on the ESRTT, a t-test with S2-S5 as dependent measure and sequence as independent measure is performed. The mean learning effect S2-S5 was larger for sequence 1 (M=38.52, SD=48.75) than for sequence 2 (M=5.81, SD=162.81), but this difference did not reach significance (t(52)=1.00, p=.32). The R6-S5 learning effect was also not significantly different for participants exposed to sequence 1 (M=27.41, SD=82.58) and those exposed to sequence 2 (M=25.80, SD=176.16), t(52)=.043, p=.97).

3.4.4 Summary of ESRTT results

There was a significant main effect of block but not of group on reaction time, nor did the interaction between group and block reach significance. However, the curves in Figure 3 show a typical learning curve for the controls but not for the dyslexics. Post hoc analysis revealed a significant difference between S2 and S5 and between S5 and R6 for the controls, but not for the dyslexics.

No significant difference was found between the two groups on our learning measures (S2-S5 and S5-R6). Attention (Bourdon-Wiersma Vigilance Test score) was significantly correlated to R6-S5 for controls but not for dyslexics. No significant main effect of sequence was found on either learning measure.

There was no significant between group difference on the explicit knowledge measure (longest correct overlap). Mean confidence rating and longest correct overlap were significantly correlated to each other but not to the procedural learning measures (R6-S5 and S2-S5). BWVT score was not significantly correlated to longest correct overlap for dyslexics nor for controls.

The sequence participants were exposed did not affect the amount of learning that occurred.

3.5 Explicit knowledge in ISRTT and ESRTT

In order to test whether the amount of explicit knowledge gained in the SRT tasks was different under implicit and explicit conditions a mixed factor ANOVA was performed with 'longest correct overlap' (the longest chunk correct present in all three attempts to reproduce the sequence) as dependent measure, task (ISRTT and ESRTT) as repeated measures factor and group as independent factor. A significant effect of SRTT type was found ($F(1,52)=13.77$, $p=.001$). The longest correct overlap was longer in the explicit condition ($M=4.83$ $SD=3.03$) than in the implicit condition ($M=3.19$ $SD=2.05$). The main effect of group did not reach significance ($F(1,52)=1.60$, $p=.21$), nor did the interaction between group and SRTT type ($F(1,52)=.77$, $p=.39$).

4. Discussion

The aim of this study was to investigate whether developmental dyslexics have an implicit learning deficit in both the language and the motor domain. We predicted dyslexics would perform worse than controls on tasks two tasks assessing implicit learning skills (artificial grammar learning and a serial reaction time task), and that they would perform equally well as controls on a task assessing explicit learning (explicit serial reaction time task). Furthermore, we predicted that the performance measure of the AGL task and the learning measures of the ISRTT task would be correlated. A correlation of participant's performance on the two tasks assessing implicit learning in different modalities would suggest that the two tasks essentially tap in to the same domain general implicit learning mechanism.

Contrary to what we expected, no significant difference was found between the dyslexic group and the control group on our learning measure in the AGL task (d') or on our learning measures in the ISRTT (S2-S4 and R6-S5). The amount of explicit knowledge gained in the ISRTT and in the ESRTT did not differ between the dyslexic and control group. Furthermore, no correlation was found between AGL performance (d') and ISRTT performance (S2-S4 and R6-S5).

The absence of the correlation between the two tasks assessing implicit learning might be due to the different nature of the learning measures used in the tasks. While in the SRTT learning is measured directly through performance, in the AGL task implicit knowledge is measured after learning has taken place. Another possibility is that implicit language learning and implicit sensorimotor learning are not two instances of the same general cognitive ability after all.

No implicit learning deficit was found in developmental dyslexics. This result is consistent with the findings of Rüsseler et al. (2006), Kelly et al. (2002) and Waber (2003), who, like us, did not find dyslexics to be impaired on tasks assessing implicit learning. However, there were indications in the present study that the dyslexic group did have difficulties with some of the tasks. First, dyslexics did not perform above chance on the AGL task, while controls did (although no significant difference was found between the two groups). Secondly, the ESRTT reaction time data of the controls revealed a typical learning curve (Figure 3) whereas the reaction times of dyslexics hardly decreased over blocks and hardly increased from block S5 to R6.

The ESRTT was performed under explicit conditions (participants were told there was a fixed sequence). Interestingly, no clear difference between the learning curves of dyslexics and controls was found in the implicit SRTT results. Thus, if dyslexics are indeed impaired on the ESRTT, this is not consistent with hypothesis that dyslexics are impaired on implicit learning. An obvious difference between the implicit and the explicit SRTT is that in the implicit SRTT participants were asked to perform only one task (pushing the buttons corresponding to stimuli on the screen), while in the explicit SRTT participants perform a triple task: they were asked to push the buttons corresponding to the stimuli, to determine whether in a block they were exposed to a random or a repeating fixed sequence (the analysis of which is beyond the scope of this paper), and to remember the fixed sequence.

As discussed in the introduction of this paper, other researchers did find implicit learning to be impaired in participants with DD, both in artificial grammar learning (Pavlidou et al., 2010) and sequence learning (Stoodley et al., 2006; Stoodley et al., 2008; Howard et al., 2006; Jiménez-Fernández et al., 2011; Sperling et al., 2004; Vicari et al., 2005). Kelly et al. (2002), who found no implicit sequence or motor response learning deficit in dyslexics, suggest that other factors such as attention may have confounded the results of others and that in those studies the deficit found was mistakenly assigned to implicit learning or automatization. In support of the idea that attention may be a confound in studies assessing implicit learning skills in dyslexics, Wimmer, Mayringer and Raberger (1999) found an impairment in dual task balancing (balancing on one foot while performing a simple verbal task) only in dyslexic children with higher ADHD scores and not in other dyslexic children. In fact when the dyslexic children with high ADHD scores were removed from the sample the dyslexic children tended to balance better than age-matched controls. What's more, in Waber et al. 's (2003) study more attention problems did seem to be associated with a response time pattern suggesting impaired implicit sequence learning, but the error pattern was not consistent with a sequence learning deficit.

Pavlidou et al. (2010) found that dyslexic children performed significantly worse than controls on an artificial grammar learning task. Obvious differences between our design and Pavlidou et al. 's design include the age of the participants (Pavlidou et al. tested children), the modality (visual), and the use of symbols instead of words. Possibly, the performance of dyslexic children in Pavlidou et al. (2010) was affected by an attention deficit. Hari and Renvall (2001) found sluggish attentional shifting and minineglect of the left visual field to influence performance of dyslexics in visual and auditory tasks. However, Rüsseler et al. (2006) tested adult dyslexics using a similar paradigm in the visual modality as Pavlidou et al. (2010) and like us found no significant deficit. Rüsseler et al.'s finding suggests that perhaps it was participant age and not attentional demands of the task that caused the result found by Pavlidou et al. (2010) to be different from ours.

4.1 Sustained attention capacity

As discussed above, there were indications that dyslexics were impaired on the AGL task and on the ESRTT, but it remains unclear whether the performance of the dyslexic group truly differed from the performance of the control group. Since attention was thought to be a possible confound in other experiments assessing implicit learning, the results of the Bourdon-Wiersma vigilance test were analyzed. Interestingly, we found the scores of dyslexics on the Bourdon-Wiersma test of sustained attention to be significantly lower than the scores of controls. Also, BWVT score was positively correlated with dyslexics' (and not with controls') performance on the AGL task (d'). This finding indicates that better sustained attention was associated with better implicit learning in the AGL task . A possible explanation for this finding is that dyslexics, having a more limited sustained attention capacity (a significantly lower BWVT score than controls)[8], have more trouble dividing their attentional resources over the tasks of coloring and listening during the AGL learning phase. In that case better sustained attention capacity will result in a higher d'. On the other hand, for controls, whose capacity to sustain attention is larger, small differences in sustained attention capacity do not lead to different d' scores.

The absence of a typical learning curve for the dyslexics in the ESRTT might also be explained by the finding that dyslexics performed worse than controls on the BWVT of sustained attention. Importantly, no difference is found between dyslexics and controls on the explicit knowledge measure in the ESRTT (length of longest chunk correct present in all three attempts to reproduce the sequence). If the dyslexics were impaired on their sustained attention capacity and not on learning, one might expect dyslexics to have lower scores than controls on the explicit knowledge measure as well. Perhaps not only dyslexics' sustained attention capacity is impaired (as indicated by the significantly lower Bourdon-Wiersma Vigilance Test score), but also (explicit) sensorimotor learning.

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[8] A person's ability to sustain attention is not necessarily equivalent to a person's attentional resources. Sustained attention is defined as "the participant's state of readiness to detect rarely and unpredictably occurring changes in the stimulus situation over extended periods of time" (Sarter & Lustig, 2009). A person may experience many lapses of attention but in the mean time be able to attend to an above average amount of stimuli at the same time. The Bourdon Wiersma Vigilance test is a test of sustained attention and not of attentional resources. Intuitively, having a greater capacity to sustain attention does help to perform better on tasks requiring a division of attentional resources.

At first glance, it seems inconsistent that sustained attention scores (BWVT) of the dyslexics were positively correlated with artificial grammar learning performance (d') and not with measures of sensorimotor learning (ISRTT: S2-S4 or R6-S5, ESRTT: S2-S5 or R6-S5). What is more, a positive correlation is found in the explicit SRTT between BWVT score and the learning measure R6-S5 in the controls but not the dyslexics. This finding indicates that better sustained attention was associated with better learning in controls, but that in dyslexics no such association was found.

There are two ways to explain the presence of the correlation for the dyslexics in the AGL and the absence of a correlation in the implicit SRTT. First, in the learning phase of the artificial grammar learning task participants are asked to color several mandala's and to listen to a stream of nonsense words. This could be considered a dual task, which, therefore, demands a division of attentional resources unlike learning in the implicit SRTT. Sustained attention capacity therefore affects performance on the AGL task but not on the less demanding implicit SRTT. In this explanation it is assumed that a person's ability to sustain attention is related to that person's ability to divide attentional resources.

A second explanation of the absence of a correlation between attention and implicit learning in the ISRT task does not assume the two 'types' of attention to be related. Possibly, the measures of learning used in the AGL task and in the ISRT task are affected by lapses in attention to different degrees. Lapses in attention (occuring more often in participants with less sustained attention capacity) may influence d' in the AGL task more than R6-S5 or S2-S4 in the implicit SRTT. This seems plausible, as the result of a lapse of attention during the test phase of the AGL task could be one wrong answer out of 48. A lapse of attention in the implicit SRTT on the other hand, can result in a temporary slowing of button pressing (or increase in error rate). Since 72 button presses per block are measured and median (not mean) reaction times are used in the analysis, the learning measure of the implicit SRTT is expected to be much less influenced by a lapse in attention than d'.

Finally, the presence of a significant correlation between sustained attention and procedural learning (R6-S5) on the ESRTT for the controls but not for the dyslexics needs to be explained. The presence of a correlation in the explicit SRT task is not very surprising. The fact that it is a triple task explains that sustained attention capacity is taxed more than in the implicit SRTT and that therefore sustained attention capacity has an effect on the amount of sensorimotor learning. However, the presence of a correlation for the controls and not for the dyslexics is surprising. Possibly, instead of dividing their attention over the different subtasks, dyslexics focussed on remembering the sequence and 'gave up' on sensorimotor learning (so that motor responses did not become faster with practice), thereby not fully taxing their attention capacity. Controls on the other hand may have divided their attentional resources efficiently over the subtasks, thereby taxing their full attention capacity. This hypothesis is supported by Smith-Spark, Fawcett, Nicolson and Fisk's (2004) finding that dyslexic participants rate themselves as having a greater tendency to over-focus than control participants do. Also, in the present study, no between group difference on the measure of explicit knowledge ('longest correct overlap') in the ESRTT was found, while the reaction time data did suggest a difference between dyslexics and controls (no learning curve was found for the dyslexic group while a typical learning curve was found for the control group).

Another explanation for the presence of a correlation between sustained attention capacity and procedural learning in the control group only is that dyslexics did not automatize the task whereas controls did. Moores and Andrade (2000) have suggested that lapses in attention influence performance on a serial reaction time task only when responses are automated. When a motor response is planned automatically, it is more difficult to inhibit at the last moment than when a motor response is planned consciously. A greater ability to sustain attention helps to notice when an automatically planned response should be inhibited, whereas consciously planned responses do not need to be inhibited. The presence of a typical learning curve for the control group only in the ESRTT as shown in Figure 3 does support the idea that only controls automated the task and that therefore sustained attention influenced their performance. In the ISRTT both the controls and the dyslexics seem to have automated their responses (see Figure 2, both groups show a typical learning curve), but as this task is much less demanding in terms of processing than the ESRTT, sustained attention is not of influence.

To sum up, even though no significant between group differences were found, there are indications that dyslexics had difficulties with the AGL task and with sensorimotor learning in the ESRTT. A deficit in the capacity to sustain attention may explain the difficulties dyslexics had with those tasks. However, the absence of a typical learning curve in the ESRTT in combination with the equal scores of dyslexics and controls on the explicit knowledge measure in the explicit SRTT suggests that a sensorimotor learning deficit may also play a role.

4.2 Attention and implicit learning

The possibility of an effect of attention on implicit learning may at first glance seem counter intuitive: paying attention to a stimulus is likely to make you aware of that stimulus. However, attention and awareness are not interchangeable concepts (as discussed in Jiang & Chun, 2003). Several studies provide an indication of attention being involved in implicit learning. Nissen and Bullemer (1987) for example, have even suggested that attention is a requirement in implicit sequence learning. The authors performed an experiment in which participants where asked to perform an SRTT under a single or dual task condition. In the dual task condition the participants were exposed to high and low frequency tones during the serial reaction time task and they were asked to count high frequency tones. While under single task condition the participants showed learning, no such learning was found in the dual task condition.

Frensch, Lin and Buchner (1998) on the other hand found that learning under a dual task condition in an SRTT does occur but does not show up in performance. Reaction times did not decrease as much over blocks under the dual task condition (SRTT with tone counting) as under the single task condition (SRTT without tone counting). But when the dual task condition was changed to a single task condition after a few blocks reaction times immediately decreased to the level of participants that had performed the entire task under the single task condition. Also, reaction times increased to a similar degree from the last structured to the first random block in participants that performed the entire task under single task condition as in participants that had performed the first few blocks under the dual task condition.

The 'type' of attention manipulated in these dual task paradigms is divided attention, which, according to Sarter and Lustig (2009), "emphasizes the allocation and the management of limited attentional resources in situations that require attention to multiple stimuli or tasks". The result of Frensch et al. indicates that having enough attentional resources is not a requirement for implicit sensorimotor learning, but that it may influence learning measures based on performance. Jiménez and Méndez (1999) found another 'aspect' of attention to be involved in implicit learning: attending selectively to part of the incoming stimuli. In an SRT task in which participants had to respond to the location of stimuli, both stimuli location and stimuli shape predicted the following stimulus location. The relation between location and shape was only learned if participants were forced to attend to shape in order to perform a secondary task (counting a target stimulus shape). Interestingly, the presence of the secondary task did not influence the amount of learning that occurred during the task.

It is conceivable that both implicit learning and attention are (mildly) affected in developmental dyslexia. The neural substrates of the deficits may even be the same or overlapping. Besides its involvement in implicit sensorimotor learning the cerebellum has been associated with shifting and orientation of attention (Akshoomoff, Courchesne, & Townsend, 1997; Allen, 1997). Furthermore, there is research suggesting that children with attention deficit hyperactivity disorder have smaller cerebellar volumes (Durston, 2003)

On the basis of our findings we cannot exclude the possibility that dyslexics are impaired on implicit learning, (sustained) attention or both. The hypothesis that dyslexics are only impaired on procedural learning cannot be fully rejected because the Bourdon-Wiersma Vigilance Test score may not be completely independent from implicit procedural learning: automatization of crossing out groups of four dots on a sheet with many groups of dots is conceivable. But the hypothesis that only sustained attention is impaired in dyslexics can also not be rejected as no significant between group differences on implicit learning measures were found and because there was a significant between group difference in BWVT score.

In the further analysis of our data, an additional step to be taken is to remove participants with the lowest BWVT scores from the analysis and see if the dyslexic group then performs above chance on the AGL task and whether an improvement is seen in the learning curve in the ESRTT. Also, the data can be reanalyzed with participants sorted in a 'low sustained attention group' and a 'high sustained attention group. But further research is needed in which effects of attentional deficits and of (implicit) procedural learning deficits can be disentangled.

A means to further explore the issue is to repeat the auditory AGL task but to remove the mandala coloring from the task. This way, the task is no longer dual and therefore charges less attentional capacity. If dyslexics perform better (above chance) on this single task design, then perhaps their sustained attention capacity acted as a confound in our dual task design and dyslexics are not impaired on implicit learning. In Rüsseler et al. (2006) for example, no distractor task was used to ensure implicit learning in the AGL task. It was even ensured participants were able to reproduce a sequence before they were exposed to the next sequence. Rüsseler et al. found no indication of an artificial grammar learning impairment in dyslexics. Adjusting the task by removing the mandala coloring is not without risk. It increases the likelihood that participants start to focus on the auditory stimuli they are exposed to and thereby the likehood that the learning that occurs is explicit instead of implicit.

Furthermore, the finding that selective attention is related to implicit learning (Jiménez & Méndez, 1999) may help us shed light on whether there is a deficit in attention or in implicit learning in developmental dyslexics. A similar paradigm as the one used by Jiménez and Méndez (1999) could be employed. A group of dyslexic participants and a group of controls can perform an SRTT in which stimulus location is predicted both by previous location and by shape. In one condition participants are only asked to respond to stimulus location by pressing the corresponding button, and in another condition participants are asked to respond to stimulus location but also to count the occurence of a target (one of four stimulus shapes). If selective attention is impaired in dyslexics, it is expected that only the controls learn how stimulus shape predicts stimulus location under dual task condition (because then they are forced to attend to shape), but performance should otherwise be equal to performance of the dyslexics. If only implicit learning is impaired on the other hand, dyslexics will perform worse than controls on implicit learning in both the single and the dual task. Independently of learning the relation between shape and location, dyslexics may also show impaired learning in the dual task condition as compared to the single task condition if their attentional resources are more limited than those of controls.

In this study we set out to find an implicit learning impairment in developmental dyslexics, but no significant differences in the performance of developmental dyslexics and controls on implicit language and sensorimotor learning tasks are found in the present study. However, there are strong indications that developmental dyslexics are impaired on an implicit language learning task and on an explicit sensorimotor learning task. However, dyslexic participants also seem to have lower capacity to sustain attention than controls, and it remains unclear whether an attention deficit, an implicit learning deficit or both cause the deviant pattern of performance of the dyslexic participants. In future research on procedural learning in dyslexia, the effects of attentional resources, the ability to sustain attention and the ability to shift attention should be carefully controlled for.

References

Akshoomoff, N. A., Courchesne, E., & Townsend, J. (1997). Attention coordination and anticipatory control. In Schmahmann, J.D. (Eds.), *The Cerebellum and Cognition* (575-598). San Diego: Academic Press.

Allen, G., Buxton, R. B., Wong, E. C., & Courchesne, E. (1997). Attentional Activation of the Cerebellum Independent of Motor Involvement. *Science, 275*, 1940-1943.

Boersma, P. (2001). Praat, a system for doing phonetics by computer. Glot International, 5:341-345.

Bourdon, B., & Wiersma, E. D. (1998). *Bourdon-Wiersma test (BWT)*. Amsterdam: Harcourt Assessment.

Brambati, S. M., Termine, C., Ruffino, M., Stella, G., Fazio, F., Cappa, S. F., et al. (2004). Regional reductions of gray matter volume in familial dyslexia. *Neurology , 63 (4)*, 742-745.

Brus, B. T., & Voeten, M. J. M. (1998). *Een-Minuut-Test, vorm A*. Lisse: Swets & Zeitlinger.

Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit Learning: news from the front. *Trends in Cognitive Sciences, 2 (10)*, 406-416.

Clegg, B. A., DiGirolamo, G. J., & Keele, S. W. (1998). Sequence learning. *Trends in Cognitive Sciences , 2 (8),* 275-281.

Denckla, M. B., & Rudel, R. (1974). Rapid "automatized" naming of pictured objects, colors, letters, and numbers by normal children. *Cortex, 10*, 186-202.

Destrebecqz, A., Peigneux, P., Laureys, S., Degueldre, C., Fiore, G. D., Aerts, J., et al. (2005). The neural correlates of implicit and explicit sequence learning: Interacting networks revealed by the process dissociation procedure. *Learning & Memory*, 12, 480-490.

De Pessemier, P., & Andries, C. (2009). *Gletschr - test voor gevorderd lezen en schrijven*. Antwerpen: Garant.

Dollaghan, C., & Campbell, T. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language and Hearing Research*, *41*, 1136-1146.

Dominey, P. F. (2005). From Sensorimotor Sequence to Grammatical Construction: Evidence from Simulation and Neurophysiology. *Adaptive Behavior, 13*, 347-361.

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., et al. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research , 199*, 61-75.

Doyon, J., Penhune, V., & Ungerleider, L. G. (2003). Distinct contribution of the cortico-striatal and corico-cerebellar systems to motor skill learning. *Neuropsychologia , 41*, 252-262.

Durston, S. (2003). A review of the biological bases of ADHD: What have we learned from imaging studies?. *Mental Retardation and Developmental Disabilities Research Reviews, 9 (3)*, 184-195.

Dutoit, T., Pagel, V., Pierret, N., Baraille, F., Van der Vreken, O. (1996). The MBROLA Project: Towards a Set of High-Quality Speech Synthesizers Free of Use for Non-Commercial Purposes. *Proceedings ICSLP'96: Vol. 3*. (pp. 1393-1396). Philadelphia.

Fawcett, A. J., & Nicolson, R. I. (1995). Persistent deficits in motor skill of children with dyslexia. *Journal of Motor Behavior, 27*, 235-240.

Fawcett, A., & Nicolson, R.I. (2004). Dyslexia: The Role of the Cerebellum. *Electronic Journal of Research in Educational Psychology. 2 (2)*, 35-58.

Field, A. (2009). *Discovering Statistics Using SPSS*. London: SAGE Publications.

Frensch, P. A., Lin, J., Buchner, A. (1998). Learning versus behavioral expression of the learned: The effects of a secondary tone-counting task on implicit learning in the serial reaction task. *Psychological Research, 61*, 83-98.

Gelman, A., & Hill, J. (2007). *Data Analysis Using Regression and Multilevel/Hierarchical Models*. New York: Cambridge University Press.

Goldberg, N. (n.d.). Intra-Individual Associations between the Serial Reaction Time Task and the Artificial Grammar Learning Task.

Gottwald, B., Mihajlovic, Z., Wilde, B., & Mehdorn, H. M. (2003). Does the cerebellum contribute to specific aspects of attention? *Neuropsychologia, 41*, 1452-1460.

Habib, M. (2000). The neurological basis of developmental dyslexia An overview and working hypothesis. *Brain, 123*, 2372-2399.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *TRENDS in Cognitive Sciences , 5*, 525-532.

Heaton, R. K. (1981). *Wisconsin Card Sorting Test manual.* Odessa, FL: Psychological Assessment Resources.

Howard, J. H., Howard, D. V., Japikse, K. C., & Eden, G. F. (2006). Dyslexics are impaired on implicit higher-order sequence learning, but not on implicit spatial context learning. *Neuropsychologia, 44*, 1131-1144.

International Dyslexia Association. (2002, 11 12). *The International Dyslexia Association*. Retrieved 12 14, 1012, from Q: What Is Dyslexia? : http://www.interdys.org/FAQWhatIs.htm

Jacoby, L. L. (1991). A Process Dissociation Framework: Separating Automatic from Intentional Uses of Memory. *Journal of Memory and Language , 30*, 513-541.

Jiang, Y., Chun, M.M. (2003). Contextual cueing: reciprocal influences between attention and implicit learning. In Jiménez, L. (Ed.), *Intention and Implicit Learning* (277-296). Amsterdam/Philadelphia: John Benjamins Publishing Company.

Jiménez, L., *Méndez, C. (1999). Which Attention Is Needed for Implicit Sequence Learning? Journal of Experimental Psychology: Learning, Memory, and Cognition, 25 (1)*, 236-259.

Jiménez-Fernández, G., Vaquero, J. M., Jiménez, L., & Defior, S. (2011). Dyslexic children show deficits in implicit sequence learning, but not in explicit sequence learning or contextual cueing. *Annals of Dyslexia , 61*, 85-110.

Kelly, S. W., Griffiths, S., & Frith, U. (2002). Evidence for Implicit Sequence *Learning in Dyslexia. Dyslexia , 8*, 43-52.

Knowlton, B. J., & Squire, L. R. (1996). Artificial grammar learning depends on acquisition of both abstract and exemplar-specific information. J. Exp. Psychol. *Learn. Mem. Cogn.* , 22, 169-181.

Kuhl, P. K. (2004). Early Language Acquisition: Cracking the Speech Code. Nature *Reviews | Neuroscience , 5*, 831-843.

Levy, D. A., Stark, C. E., & Squire, L. R. (2004). Intact Conceptual Priming in the Absence of Declarative Memory. *Psychological Science , 15 (10)*, 680-686.

Lieberman, M. D., Chang, G. Y., Chiao, J., Bookheimer, S. Y., & Knowlton, B. J. (2004). An event-related fMRI study of artificial grammar learning in a balanced chunk strength design. *J. Cogn. Neurosci. , 16*, 427-238.

Macmillan, N. A., & Creelman, C. D. (2005). *Detection Theory: A User's Guide*. USA: Lawrence Erlbaum Associates.

Menghini, D., Hagberg, G. E., Caltagirone, C., Petrosini, L., & Vicari, S. (2006). Implicit learning deficits in dyslexic adults: An fMRI study. *NeuroImage , 33*, 1218-1226.

Moores, E., & Andrade, J. (2000). Ability of dyslexic and control teenagers to sustain attention and inhibit responses. *European Journal of Cognitive Psychology , 12 (4)*, 520-540.

Mueller, J. L., Bahlmann, J., & Friederici, A. D. Learnability of Embedded Syntactic Structures Depends on Prosodic Cues . *Cognitive science , 34 (3)*, 338-349.

Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research? *Cognition , 35*, 159-182.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (1995). Time estimation deficits in developmental dyslexia: Evidence of cerebellar involvement. *Proceedings of the Royal Society B, 259*, 43-47.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: the cerebellar deficit hypothesis. *TRENDS in Neurosciences , 24 (9)*, 508-511.

Nissen, M. J., & Bullemer, P. (1987). Attentional Requirements of Learning: Evidence from Performance Measures. *Cognitive Psychology , 19*, 1-32.

Pavlidou, E. V., Kelly, M. L., & Williams, J. M. (2010). Do Children with Developmental Dyslexia Have Impairments in Implicit Learning? *Dyslexia , 16*, 143-161.

(2012). Proefbunny. *Proefbunny.nl.* Retrieved from www.proefbunny.nl

Rüsseler, J., Gerth, I., & Münte, T. F. (2006). Implicit Learning is Intact in Adult Developmental Dyslexic Readers: Evidence from the Serial Reaction Time Task and Artificial Grammar Learning . *Journal of Clinical and Experimental Neuropsychology , 28 (5)*, 808-827 .

Rae, C., Lee, M. A., Dixon, R. M., Blamire, A. M., Thompson, C. H., Styles, P., et al. (1998). Metabolic abnormalities in developmental dyslexia detected by 1H magnetic resonance spectroscopy. *The Lancet , 351*, 1849-1852.

Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Current opinion in neurobiology, 13 (2)*, 212-218.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain , 126 (4)*, 841-865.

Rauch, S. L., Savage, C. R., Brown, H. D., Curran, T., Alpert, N. M., Kendrick, A., et al. (1995). A PET Investigation of Implicit and Explicit Sequence Learning. *Human Brain Mapping , 3*, 271-286.

Reber, A. S. (1989). Implicit Learning and Tacit Knowledge. *Journal of experimental psychology, 118*, 219-235.

Reber, A. S. (1967). Implicit learning of artificial grammars. *J. Verb. Learn. Verb. Behav.*, 6, 855-863.

Rieckmann, A., & Bäckman, L. (2009). Implicit learning in aging: extant patterns and new directions. Neuropsychology Review, 19, 490-503.

Rüsseler, J., Gerth, I., & Münte, T.F. (2006). Implicit Learning is Intact in Adult Developmental Dyslexic Readers: Evidence from the Serial Reaction Time Task and Artificial Grammar Learning. *Journal of Clinical and Experimental Neuropsychology, 28 (5)*, 808-827.

Sarter, M., & Lustig, C. (2007). Attention and learning and memory. Squire, L. R. (Ed.), *Encyclopedia of Neuroscience*. Oxford: Elsevier.

Skosnik, P.D., Mirza, F., Gitelman, D. R., Parrish, T. B., Mesulam, M-M., & Reber, P. J. (2002). Neural Correlates of Artificial Grammar Learning. *NeuroImage, 17*, 1306-1314.

Smith-Spark, J. H., Fawcett, A. J., Nicolson, R. I., & Fisk, J. E. (2004). Dyslexic students have more everyday cognitive lapses. *Memory , 12 (2)*, 174-182.

Sperling, A. J., Lu, Z.-L., & Manis, F. R. (2004). Slower Implicit Categorical Learning in Adult Poor Readers *. Annals of Dyslexia , 2004* (*2)*, 281-303.

Squire, L. R. (1986). Mechanisms of Memory. *Science, New Series , 232 (4758)*, 1612-1619.

Squire, L. R. (2004). Memory systems of the brain: A brief history and current perspective. *Neurobiology of Learning and Memory , 82*, 171-177.

Squire, L. R., & Zola-Morgan, S. (1991). The Medial Temporal Lobe Memory System. *Science, New Series , 253 (526)*, 1380-1386.

Stanovich, K. E. (2001). Explaining the Differences Between the Dyslexics and the Garden-Variety Poor Reader: The Phonological-Core Variable-Difference Model. *Journal of learning disabilities, 21 (10),* 590-604.

Stein, J. (2001). The Magnocellular Theory of Developmental Dyslexia. *Dyslexia, 7*, 12-36.

Stevens, J. (1996). *Applied Multivariate Statistics for the Social Sciences.* Mahwah, New Jersey, USA: Lawrence Erlbaum Associates.

Stoodley, C. J., & Stein, J. F. (2011). The cerebellum and dyslexia. *Cortex , 47*, 101-116.

Stoodley, C. J., Harrison, E. P., & Stein, J. F. (2006). Implicit Learning and Tacit Knowledge. *Neuropsychologia, 44*, 795-798.

Stoodley, C. J., Ray, N. J., Jack, A., & Stein, J. F. (2008). Implicit learning in control, dyslexic, and garden-variety poor readers. *Annals of the New York Academy of Sciences*, 1145, 173-183.

Tallal, P. (1980). Auditory Temporal Perception, Phonics, and Reading Disabilities in Children. *Brain and Language, 9*, 182-198.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, S., Nagarajan, S. S., et al. (1996). Language Comprehension in Language-Learning Impaired Children Improved with Acoustically Modified Speech. *Science , 271*, 81-84.

Thurstone, L. L. (1938). *Primary mental abilities*. Chicago: Universtiy of Chicago Press.

Ullman, M. T. (2004). Contributions of memory circuits to language: the declarative/procedural model. *Cognition , 92*, 231-270.

Van den Bos, K. P. , Lutje Spelberg, H. C., Scheepstra, A. J. M., & de Vries, J. R. (1994). *De Klepel (pseudowoordentest)*. Lisse: Swets & Zeitlinger.

Vicari, S., Finzi, A., Menghini, D., Marotta, L., Baldi, S., & Petrosini, L. (2005). Do children with developmental dyslexia have an implicit learning deficit? *Journal of Neurology, Neurosurgery and Psychiatry , 76*, 1392-1397.

Veenker, T.J.G. (2012). *The Zep Experiment Control Application* (Version 0.18) [Computer software]. Utrecht Institute of Linguistics OTS, Utrecht University. Available from http://www.hum.uu.nl/uilots/lab/zep/

Waber, D. P., Marcus, D. J., Forbes, P. W., Bellinger, D. C., Weiler, M. D., Sorensen, L. G., et al. (2003). Motor sequence learning and reading ability: Is poor reading associated with sequencing deficits? *Journal of Experimental Child Psychology, 84*, 338-354.

Wechsler, D. (2000). In Uterwijk J. (Ed.), *WAIS-III Nederlandstalige bewerking*. Lisse: Swets Test Publishers.

Wijnen, F.N.K. (2013). Acquisition of linguistic categories: cross-domain convergences. In Bolhuis, J., & Everaert, M. (Eds.), *Birdsong, Speech and Language: Exploring the Evolution of Mind and Brain*.

Wilsenbach, C. (2006). Developmental Dyslexia and Specific Language Impairment. The same or different? In C. Wilsenbach, *Syntactic Processing in*

Developmental Dyslexia and in Specific Language Impairment (pp. 7-10). Utrecht: LOT.

Wimmer, H., Mayringer, H., & Raberger, T. (1999). Reading and Dual-Task Balancing : Evidence Against the Automatization Deficit Explanation of Developmental Dyslexia . *Journal of Learning Disabilities , 32*, 473-478.

Appendix 1 - Overview of neuropsychological tests

Eén-minuut-test (EMT) (Brus & Voeten, 1973). The participant has to read out loud as many words as possible in one minute. The number of words the participant reads correctly is measured.

Klepel (van den Bos et al., 1994). The participant has to read out loud as many nonsense words as possible within two minutes. The number of words the participant reads correctly is measured.

Spelling test (De Pessemier, 2009). The participant has to listen to words and write them down. At the end of the test participants can correct their answers using a blue pen and then rate their answer in terms of how certain they are about its correctness.

Nonword repetition task (NWRT) (Dollaghan and Campbell, 1998). Dutch version. The participants were exposed auditorily to 40 nonwords and were asked to repeat each nonword. The number of words the participant repeats correctly is measured.

Rapid naming tests (RAN) (Denckla & Rudel, 1974). Three standard RAN tasks (digits, letters, objects) are carried out. The participant is asked to name columns of digits (1, 4, 5, 6, 8), letters (r, k, t, s, f), and line-drawn pictured objects (dog, fish, candle, car, hammer) as fast as possible.

WAIS - III IQ test. The WAIS - III test is a standard test of IQ (Wechsler, 2000). The test provides scores for Verbal IQ, Performance IQ, and Full Scale IQ, along with four secondary indices (Verbal Comprehension, Working Memory, Perceptual Organization, and Processing Speed).

Verbal competence test. In this test participants were given 20 word pairs (e.g. ‘poem’ and ‘statue’) and asked to describe the similarity between the two items of each pair. Each answer was scored as correct (2), partially correct/incomplete (1) or incorrect (0).

The time estimation task. This time estimation task was identical to the one described by Nicolson, Fawcett and Dean (1995). In this task the participant was presented with pairs of tones, and instructed to indicate for each tone pair whether the second tone was shorter or longer than the first one by pressing the button indicating 'longer' or the button indicating 'shorter'. D' was calculated and used as performance measure.

Bead threading (Fawcett & Nicolson, 1996). The participants were given a string and 15 wooden beads. They were instructed to thread the beads as fast as possible, holding the string in the dominant hand. The relevant measure was the time it took to thread the 15 beads.

Bourdon-Wiersma vigilance test (BWVT) (Bourdon & Wiersma, 1998). During the BWVT the participant is provided a sheet with 50 rows, each containing 25 groups of three, four, or five dots in varying configurations. Participants are asked to strike through all groups of four dots as accurately and as quickly as possible. The score is based on the time it takes the participant to complete the 50 rows and the number of omissions and errors.

Category Fluency Test (Thurstone, 1938). In this task participants were asked to generate as many words in the category 'animals' they could in one minute. The amount of animals named correctly was the performance measure. Naming the same animal more than once was counted as error. Also, when a subcategory (e.g. bird) had been named, naming any animal within that category was counted as error.

Wisconsin Card Sorting Test. In the WCST (Heaton, 1981) the participants were first shown 4 stimulus cards with different shapes (crosses, circles, triangles or stars) in various colors (red, blue, yellow, or green) and numbers (1, 2, 3 or 4). The participant is asked to sort a response card under the stimulus card he or she thinks is correct. After each response the participant is provided feedback ('correct' or 'incorrect'). No other instructions are given during the test. After 10 consecutive correct responses the criterion for sorting is changed (e.g. from shape to color). The test continues until the participant has either completed 6 categories or has used all 128 cards. In the present study the number of perseveration errors (WCST PE) and the number of categories completed (WCST NC) were measured.

Appendix 2 - AGL task: grammar and stimuli

Artificial Grammar

The artificial grammar used to construct the grammatical sequences for the learning and test phase of the AGL task complied to the rule AABB (Mueller, Bahlmann, & Friederici, 2010). Hierarchical processing was achieved by implementing dependencies between category A and B nonword pairs (eg. A1-B1) (see Figure 4).

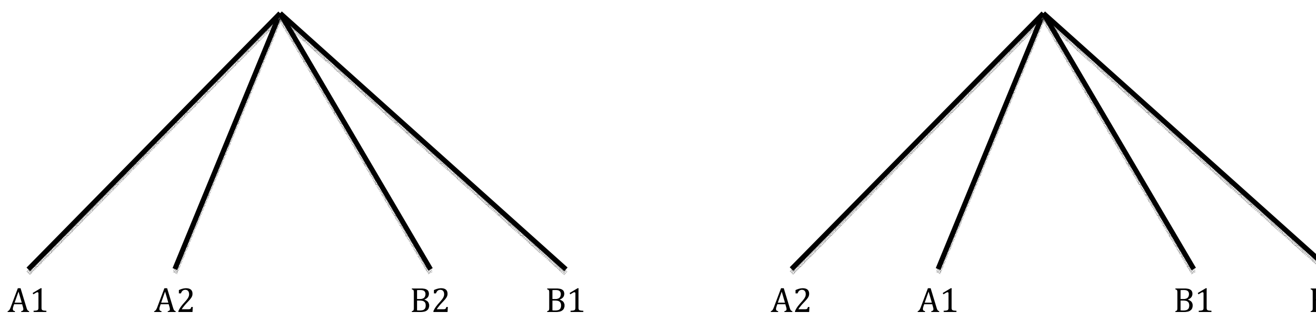


Figure 4 Grammatical sequences

Ungrammatical strings were formed by a violation of either category (e.g. A1B2B2B1), a violation of dependency (e.g. A1A2B1B1) or both (e.g. A2A1A2B2). The dependency violations were subdivided in inner (e.g. A1A2B1B1) and outer (e.g. A2A2B2B1) dependency violations.

Stimuli

The stimuli that made up the artificial sentences in the AGL task existed of eight CCVC nonwords that complied to phonotactic constraints of Dutch (see Table 3). Words with the vowel /o/ belonged to category A, and words with the vowel /e/ belonged to category B. Dependencies between A-B pairs were determined by voicing of the first consonant in the onset cluster. The nonwords in the A1-B1 pair started with /p/ or /t/, and nonwords in the pair A2-B2 started with /b/ or /d/. The second consonant of the words was always either /w/ or /r/. The final consonant was not fixed. The stimuli were produced using the MBROLA artificial speech synthesizer (Dutoit, 1997).

prot	A1
twok	A1
prel	B1
twel	B1
brong	A2
dwot	A2
breg	B2
dres	B2

Table 3 Overview of nonwords used in the AGL task

To mark the boundaries of the artificial sentences produced with the nonwords prosodic cues were added. In accordance with each sentence position pitch was adjusted using PRAAT (Boersma, 1992). Words in 1st position had a frequency of 115-125 Hz, words in 2nd position a frequency of 95-85 Hz, words in 3rd position a frequency of 95-115 Hz, and words in 4th position 136-76 Hz. All sounds were converted to a sample frequency of 48000 Hz. Four pauses were added between the nonwords making up an artificial sentence (see Figure 5).

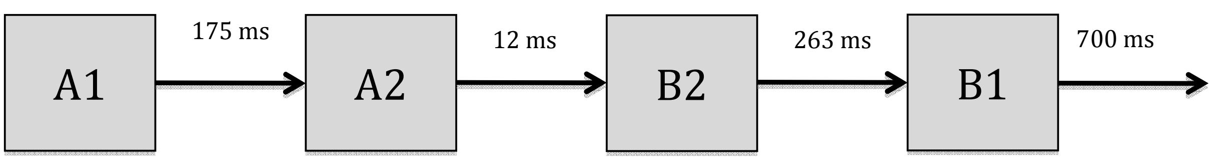
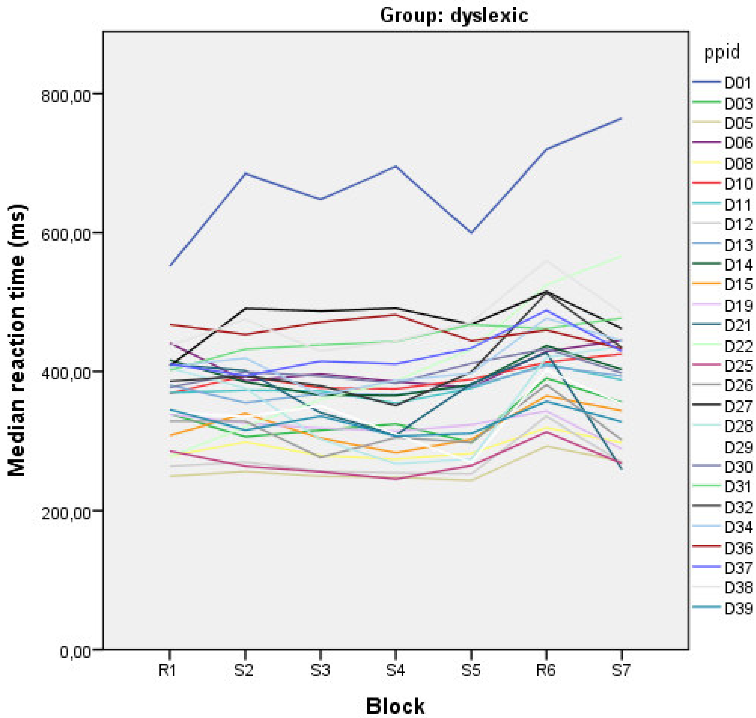


Figure 5 Pauses between nonwords

The four nonword sequences used in the learning phase and the test phase of the AGL task were randomly generated. There were 64 possible grammatical sequences. A constraint was that half of the grammatical sequences in the test phase were old (participants had already been exposed to these sequences in the learning phase). Also, all grammatical sequences with repetitions were old.

Appendix 3 Individual reaction time data ISRTT

The graphs below show median reaction times in each block of the ISRTT for each participant separately and in separate graphs for the dyslexic group and the control group.


Group: dyslexic
Median reaction time (ms)
800,00
600,00
400,00
200,00
0,00
R1
S2
S3
S4
S5
R6
S7
Block
ppid
D01
D03
D05
D06
D08
D10
D11
D12
D13
D14
D15
D19
D21
D22
D25
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D27
D28
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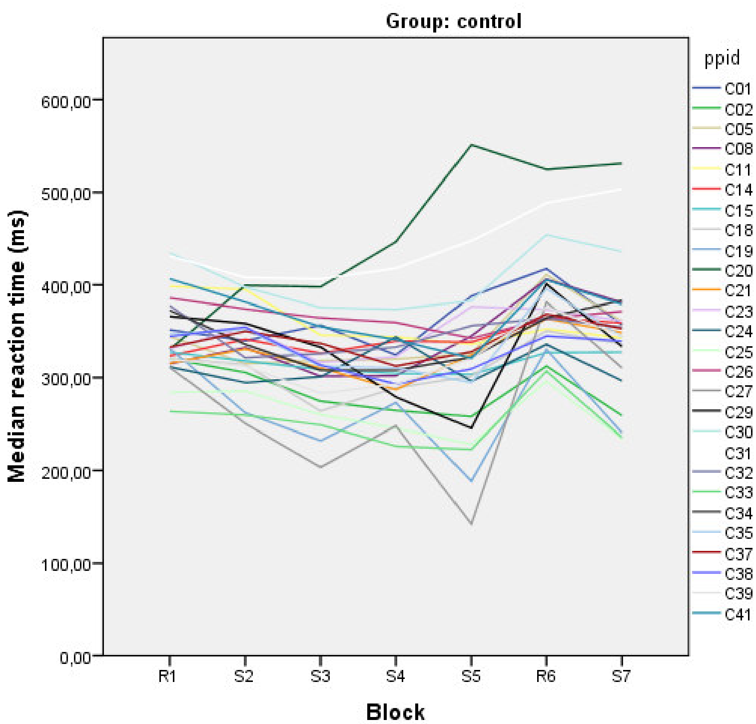
D36
D37
D38
D39


Group: control
Median reaction time (ms)
600,00
500,00
400,00
300,00
200,00
100,00
0,00
R1
S2
S3
S4
S5
R6
S7
Block
ppid
C01
C02
C05
C08
C11
C14
C15
C18
C19
C20
C21
C23
C24
C25
C26
C27
C29
C30
C31
C32
C33
C34
C35
C37
C38
C39
C41

Appendix 4 Individual reaction time data ESRTT

The graphs below show median reaction times in each block of the ESRTT for each participant separately and in separate graphs for the dyslexic group and the control group.