Hidden in plain sight

Impaired visual statistical learning might contribute to reading

difficulties in dyslexia

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Lokaverkefni til B.S. gráðu

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Preface

The study was conducted in collaboration with Elín Ástrós Þórarinsdóttir, Hilda Björk Daníelsdóttir, and Margrét Guðmundsdóttir under the guidance and in cooperation with Dr. Heiða María Sigurðardóttir and Dr. Árni Kristjánsson. I would like to thank my colleagues whose commitment to the study was unparalleled. Special thanks go out to our excellent advisors Heiða María Sigurðardóttir and Árni Kristjánsson without whom this BSc thesis could never have been written. They provided unyielding support and showed us patience through thick and thin. I would like to express my gratitude towards Heiða who provided me with invaluable guidance in the art of programming and in the writing of this thesis. Last but not least, I would like to thank Dr. Ómar Ingi Jóhannesson, who also aided me in the art of programming and was always willing to lend a helping hand. This BSc thesis is dedicated to the loving memory of my fiancée Tinna Ingólfsdóttir and my grandmother Helga Finnsdóttir. Your relentless support through the years will not be forgotten. Thank you all.

Objective: The objective of the current study was to determine if dyslexics show deficiencies in visual statistical learning (VSL). Research suggests that reading abilities and literacy-related skills vary in accordance with people´s capacity for VSL. Therefore, it would be expected that an impaired capacity for VSL might contribute to the reading difficulties of dyslexics. Evidence for this comes from research revealing that the visual word form area, a brain region involved in the processing of words, is recruited in VSL. This brain region has consistently been found to be hypoactive in dyslexics. *Method:* 40 diagnosed dyslexics and 40 matched typical readers participated in the study. Two participants that misunderstood the instructions and their matched counterparts were excluded. Learning was measured with a visual test of temporal statistical learning and a shape recognition control test. A questionnaire assessed whether VSL was explicit to any degree. *Results:* Dyslexics are impaired in VSL about temporal regularities in comparison to typical readers. *Conclusion:* Reading difficulties in dyslexia might partially be caused by visual statistical learning deficits. The hypoactivity of the visual word form area in dyslexics could reflect a failure to recycle the region to the processing of words through the mediation of a perceptual statistical learning mechanism.

Developmental dyslexia is defined as a specific developmental disorder that is characterized by impairments in reading, writing and spelling that are not directly caused by impairments in intelligence, gross neurological deficits, inadequate schooling or uncorrected visual or auditory difficulties (American Psychiatric Association, 2000; Lyon, Shaywitz, & Shaywitz, 2003; Schulte-Körne & Bruder, 2010). The most commonly accepted theory of dyslexia states that it is a hereditary disorder of language that is caused by cognitive deficits in phonological processing, which refers to the way phonological information is utilized in processing written and oral language (Catts, 1989; Snowling, 2001). Research has shown that dyslexics have difficulties in mental word representation and speech sound manipulation which impair their ability to decode written words and letters into speech sounds. This deficit in phonological processing leads to the inaccurate word identification and reading difficulties found in dyslexics (Du & Kelly, 2013; Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, the underlying cause of this deficit in phonological processing and the mechanism by which it functions is still unknown and warrants additional research (Norton, Beach, & Gabrieli, 2015; Vellutino et al., 2004).

In recent years a number of new theories suggest that dyslexia might be a sensory dysfunction, particularly visual. These theories rule out primary sensory disorders (e.g., acuity loss) as a cause in dyslexia while still recognizing the possibility that sensory processing problems might underlie the disorder. This line of research is increasingly implicating visual, visual attentional and visuomotor processes in reading difficulties (see e.g., Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Gori & Facoetti, 2014; Harrar et al., 2014). These theories remain highly controversial and warrant further longitudinal research (Goswami, 2015). Although the evidence for these theories is inconclusive they raise the point that reading is largely and inherently a visual task. Reading is most probably a cultural development that required the adoption of other skills and mechanisms that human kind has evolved over the species' history. Reading requires that shapes of letters and words are analyzed, discriminated from each other, recognized and connected to semantic information stored in memory (Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). It is hypothetically possible that a deficit in any of these stages of visual processing could lead to the reading impairments witnessed in dyslexia.

Statistical learning (SL) is a type of implicit perceptual learning that has recently been implicated in the ability to read accurately. Studies have found reading abilities and literacy-

related skills vary in accordance with people´s capacity for SL. Children and adults that show better capacity for SL also show higher levels of reading abilities and literacy-related skills (Arciuli & Simpson, 2012b; Spencer, Kaschak, Jones, & Lonigan, 2014). Recent neurological evidence show that SL recruits word selective areas of the visual cortex that has consistently been found to be impaired in people with dyslexia (Turk-Browne, Scholl, Chun, & Johnson, 2009). In this study we set out to determine whether a lower than usual capacity for SL might be a contributing factor to dyslexia.

Statistical learning: General assessment

In cognitive neuroscience and cognitive psychology SL refers to the brain´s capacity for learning and extracting regularities of how features and object co-occur in the environment, that occurs without intent or conscious awareness (Fiser & Aslin, 2001; Perruchet & Pacton, 2006; Turk-Browne, 2012b; Turk-Browne et al., 2009). SL therefore refers to the automatic detection and extraction of regularities in the environment by using statistical information of how frequently certain objects co-occur (Musz, Weber, & Thompson-Schill, 2015; Turk-Browne, Jungé, & Scholl, 2005).

SL is critical when extracting information from noisy environments over multiple exposures (Schapiro & Turk-Browne, 2015). When learning to segment the spoken words in a second language or when detecting object borders in a novel scene, SL enables us to acquire structure in such noisy environments by segmenting the environment into "units" (Turk-Browne et al., 2009). Such learning might be an important factor in object recognition (Oliva & Torralba, 2007) and in how the visual system detects and represents higher-order units of perception, such as words, scenes and events (Turk-Browne, 2012a; Turk-Browne et al., 2009).

Many researchers view SL as a domain-general mechanism that functions in a diverse set of learning situations and over multiple sensory modalities (e.g., Bulf, Johnson, & Valenza, 2011; Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002). There is some evidence for this showing that SL operates similarly across linguistic and nonlinguistic stimuli (Evans, Saffran, & Robe-Torres, 2009). Furthermore, SL appears to be important in auditory processing (Saffran, Aslin, & Newport, 1996), visual processing (Fiser & Aslin, 2001) and tactile processing (Conway & Christiansen, 2005). SL also appears to take place in both human adults and infants (Bulf et al., 2011; Kirkham et al., 2002; Saffran et al., 1996) as well as in nonhuman primates (Hauser, Newport, & Aslin, 2001; Newport, Hauser, Spaepen, & Aslin, 2004). That

said, there is also evidence that SL might be modality constrained in certain important ways. For example, it appears that SL might entail a learning advantage in the auditory domain compared to other senses and that SL is most effective in the auditory domain for the last part of the stimulus sequence (Conway & Christiansen, 2005). It would therefore appear that SL is a domain-general mechanism that functions with domain-specific constraints.

Statistical learning: Historical background

Research on SL began in the auditory domain in the last decade of the twentieth century, in the realm of language acquisition. In a seminal study Saffran et al. (1996) proposed that infants use statistical regularities to locate word boundaries in the auditory speech stream. They exposed eight-month-old infants to a speech stream that contained syllables organized into four pseudo-words. The syllables were played without any pause between them so the only factor that defined word boundaries were statistical probabilities of certain syllables co-occurring over time. Saffran et al. (1996) found that after only two minutes of exposure to the speech stream the infants showed knowledge of pseudo-words by expressing more familiarity with them than other non-words – containing the same syllables as the pseudo-words but in sequence that the infants were never exposed to. The infants listened longer to the novel non-words than the familiar pseudo-words, indicating that they were sensitive to the difference in statistical probabilities. Saffran et al. (1996) concluded that statistical learning might therefore be important in word learning and in segmenting speech.

Visual statistical learning of temporal regularities

Although the roots of SL research can be traced to studies in the auditory domain, interest in the role that SL plays in the visual domain of perception has grown exponentially over the last 14 years. This line of research has shown that SL occurs in vision for both spatial (Chun & Jiang, 1998; Fiser & Aslin, 2001) and temporal regularities (Fiser & Aslin, 2002; Kirkham et al., 2002).

Visual statistical learning (VSL) about temporal regularities emerges in vision because events and actions appear to us in a sequential progression of information. For example, going to the library involves a sequential progression; driving, parking, searching and reading. Temporal regularities also emerge because our eyes gather information from specific points in

space distributed over time. Our eyes thus create temporal sequences in vision when we move them around the environment (Turk-Browne, 2012a)

The method used to test temporal VSL in the laboratory is an elaboration of the experimental design used in the original studies on auditory SL (Turk-Browne et al., 2005). Analogous to the study by Saffran et al. (1996) the temporal VSL paradigm most often involves showing observers a continuous stream of shapes, one shape appearing at a time (e.g., ABGHUDTKIABGTKIHUD…). Unbeknownst to the observers the stream (called the familiarization stream) is made up of shape triplets (e.g., ABG, TKI, HUD). Shapes within triplets always appear together in the same sequence but the order of triplets is randomized. Because all shapes are separated by a pause of equal length the only cue indicating the existence of triplets are the statistical regularities of co-occurring shapes in the stream. These statistical regularities are expressed in terms of the transitional probability, $P(B|A)$. The transitional probability is defined as the probability of event B occurring after event A (Arciuli & Simpson, 2012b). Because shapes within triplets always appear sequentially in the same order they have a higher transitional probability (TP = 1) than shapes between triplets (TP = 0.33). These transitional probabilities are the sole governing factor of triplet boundaries. After exposing the observers to the stream for a certain amount of time, most often while engaged in a cover task, they are surprised with a two-interval forced-choice test. This test pits the triplets previously shown against foil sequences containing the same shapes but in a sequence not previously seen before (e.g., ABG vs BGA). Observers are asked to judge which of two occurred previously. Since each shape was presented an equal number of times, any preference for triplets over foils indicates learning of the underlying triplet structure based on the statistical information found in the shape sequence. Additionally, response time measures are used to assess temporal VSL. This method involves asking the participants to observe the familiarization stream as previously described. They are then asked to identify a target shape from the familiarization stream that appears sequentially along with other shapes. Each shape is either preceded by a shape that it was paired with or another foil shape that is was not paired with. When the target shape is preceded by the paired shape this leads to speeded responses for the target shape but not when the preceding shape was a foil, indicating that the first shape in the pair came to predict the second as a consequence of VSL (Turk-Browne & Scholl, 2009).

Fiser and Aslin (2002) were among the first to utilize the temporal VSL paradigm. They found that VSL occurred automatically with mere exposure to temporal regularities. Observers

correctly identified 95% of the triplets without expressing explicit familiarity with them, indicating a strong SL effect in visual processing. More recent research using the paradigm has shown that although VSL is implicit it might require selective attentional processes to task relevant objects in order to take place. In a study by Turk-Browne et al. (2005) VSL occurred only for objects selectively attended to whilst engaged in a cover task but not for other task irrelevant objects. Research using the paradigm has furthermore found evidence that VSL is consistent over long periods of time (Arciuli & Simpson, 2012a), functions at multiple levels of complexity either binding together features within objects or forming associations between objects (Turk-Browne, Isola, Scholl, & Treat, 2008), can occur for non-adjacent objects (Newport et al., 2004) and can transfer information regarding regularities bi-directionally between spatial and temporal contexts (Turk-Browne & Scholl, 2009). It is still debated whether SL forms abstract object representations that are resistant to changes in surface features or whether it forms stimuli-specific object representations that require a precise match between visual input and representation (e.g., Otsuka, Nishiyama, Nakahara, & Kawaguchi, 2013; Turk-Browne et al., 2005).

Visual statistical learning: Neurological substrates

Research on the neurological basis of VSL has found evidence for coding of temporal regularities in the brain at the level of single neurons in the inferotemporal cortex (ITC) (Meyer & Olson, 2011; Meyer, Ramachandran, & Olson, 2014). The ITC is a region located in the ventral visual pathway (VVP), a collection of visual areas in the brain critical in the neurological representation of objects (Peissig & Tarr, 2007). ITC neurons selectively respond to images of complex objects (Gross, Bender, & Rocha-Miranda, 1969; Gross, Rocha-Miranda, & Bender, 1972; Quiroga, Reddy, Kreiman, Koch, & Fried, 2005) and evidence suggest that object representations in the ITC are established by the combined firing rate of multiple neurons in the ITC selective to the same object class (Tanaka, 1996). Single-neuron recordings in the ITC of macaques have found that repeated exposure to two objects close together in time leads to a pair coding of the two objects, in which neurons that selectively respond to one object also begin to respond to the other object (Erickson & Desimone, 1999; Miyashita, 1988).

Findings such as these indicating the ITC in the coding of temporal regularities led Meyer and Olson (2011) to suggest that ITC is a key brain region for VSL. They exposed macaques to a fixed sequence of image pairs separated by short intervals. The first image always

preceded the second image in a pair and was therefore highly predictive of the appearance of second shape. They found that after prolonged exposure the appearance of the first image consistently led to a weaker neural response to the presentation of the second image. This prediction suppression effect for the second image was contrasted with a transitional surprise effect that arose when the first image in a pair was subsequently followed by a non-paired image, which had never been paired with it, leading to a stronger neural response for the "surprise" image. This suggests that ITC neurons might acquire knowledge of transitional probabilities by either suppressing neural activity for the predicted stimuli or by giving salience to surprising and unpredicted transitions (Meyer & Olson, 2011). In a follow up study Meyer et al. (2014) replicated these findings using more complex transitions and thereby indicating that response suppression and surprise enhancement might be a viable neural mechanism for the coding of relatively complex visual statistical regularities. However, in both studies they were unable to elucidate which of the two processes, suppression or enhancement, is more important for VSL (Meyer et al., 2014).

Other regions of the VVP have been suggested as possible brain regions mediating VSL. Most notably, the perirhinal cortex (PRC) of the medial temporal lobe (MTL) has been found to contain more pair coding neurons than the ITC (Naya, Yoshida, & Miyashita, 2003). Indeed, the PRC seems like a probable location since learning in PRC occurs faster than in the ITC and processing in the PRC is necessary for pair coding to take place in the ITC (Schapiro & Turk-Browne, 2015).

A similar line of research using functional magnetic resonance imaging (fMRI) has found that VSL does in fact recruit the MTL and associated areas, such as the hippocampus, and other known memory systems, such as caudate of the striatum. It has also been found to recruit object and word selective regions of the ventral visual cortex, including the visual word form area. This pattern of brain activity was found to occur with only a few repetitions of statistically structured triplet-sequences and occurred without conscious awareness. This indicates that the neural mechanisms that mediate VSL are both fast and operate without conscious awareness or explicit instruction to learn. Importantly, the activity seen in the ventral visual cortex indicates that VSL functions at the level of visual processing and confers merit to research implicating the VVP in such processing (Turk-Browne et al., 2009).

More recently, Schapiro, Kustner, and Turk-Browne (2012) investigated how object representations in cortical and MTL regions are shaped by exposure to statistical regularities.

They found that when complex multivariate patterns co-occurred as pairs in a continuous sequential stream it led to increased similarity in their constituent neural representations. This increase in object representation similarity was found in the PRC, parahippocampal cortex, subiculum, areas CA1, CA2, CA3 of the hippocampus and dentate gyrus. It therefore seems that the aforementioned regions encode regularities by increasing the representation similarity of co-occurring objects analogous to neurons in the ITC. Most regions showed an equal increase in representational similarity in both members of a pair whereas regions CA2, CA3 and the dentate gyrus changed more for the first member of a pair. Thereby making the first member of a pair predictive of the second and not vice versa. These findings suggest that object representations in the MTL allow for statistical learning by changing in accordance with temporal regularities in the environment (Schapiro et al., 2012). Other studies have found that the MTL is involved in learning of temporal regularities with high predictability whereas the temporal parietal junction is recruited for both spatial and temporal regularities when predictability is low (Schapiro & Turk-Browne, 2015).

Frost, Armstrong, Siegelman, and Christiansen (2015) suggest that the MTL might indirectly modulate SL for all sensory modalities. This corresponds to behavioral evidence suggesting that SL is both domain-general and within-modality constrained (Conway & Christiansen, 2005). The domain-general aspect of SL could therefore originate in the MTL whereas within-modality constraints could derive from the modality specific functioning of the sensory cortices. This would mean that in the case of VSL a feedback process between the MTL and ventral visual cortex would be required. This directionality seems plausible given that processing in MTL occurs before processing in ICT (Schapiro & Turk-Browne, 2015). Further evidence for this comes from research on a patient with bilateral hippocampal loss and broad MTL damage who was totally impaired in both auditory and visual SL (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014). An alternative explanation suggested by Frost et al. (2015) is that modality-specific sensory cortices might directly operate on the MTL and related cortex to form domain-general representations. Under this view localized computations in the sensory cortices would suffice for SL in specific modalities. Evidence for this alternative directionality comes from studies that show significant domain-specific SL in patients despite damage to the hippocampus (e.g., Knowlton, Ramus, & Squire, 1992).

Research on the neural substrates of VSL has thus identified some of the key brain regions thought to mediate VSL but the precise directionality of its neural mechanism is still

debated. Current neurobiological evidence suggests that SL entails computations carried out within specific modalities that are either modulated or combined by a multidomain system, such as the MTL. Importantly, evidence is accumulating that localized object and word selective regions of the VVP are recruited in the encoding of visual statistical regularities (Meyer & Olson, 2011; Meyer et al., 2014; Turk-Browne et al., 2009). Which is of seminal importance given that VSL has recently been linked to word processing and reading ability in the general population.

Statistical learning: Reading ability and developmental dyslexia

The reading impairments seen in developmental dyslexia are generally attributed to a deficit in phonological processing, the way phonological information is utilized in processing written and oral language (Catts, 1989; Snowling, 2001). When learning to read we must learn the phonological structure of words for accurate mapping of letters to sounds (Norton et al., 2015). This ability to use speech codes to mentally represent words and parts of words has frequently been found to be impaired in dyslexics and is most commonly identified as the cause for inaccurate word identification found in dyslexia (Du & Kelly, 2013; Vellutino et al., 2004). It is, however, unlikely that a single deficit causes dyslexia. Reading involves multiple linguistic, visual and attentional processes and dyslexia is most likely caused by a varied pattern of deficits (Norton et al., 2015).

A growing body of research indicates that accurate reading might reflect an ability to detect statistical regularities in written language (Arciuli & Simpson, 2012b; Arciuli & von Koss Torkildsen, 2012; Baker, Olson, & Behrmann, 2004; Spencer et al., 2014). Under this view, the mapping between letters and sounds in a language can be thought of as probabilistic. Since children are not explicitly taught all such mappings they must be sensitive to contextual cues indicating such letter-sound correspondences. For example, in English the letter "c" is often linked to the phoneme /k/. The letter can, however, be mapped onto other phonemes such as /s/. Over time, children learn that when certain letters co-occur certain phonemes map onto these letters but not others. When a word begins with the letter "c" it is commonly followed by the letter "i" with /s/ as its corresponding phoneme. Based on exposure to such statistical regularities children might accurately learn letter-sound mappings without explicit instruction or conscious awareness (Arciuli & Simpson, 2012b; Arciuli & von Koss Torkildsen, 2012). Similarly, children might use other statistical regularities in written language when learning to

read, such as being sensitive to regularities about legal combinations of letters (Arciuli & Simpson, 2012b; Deacon, Conrad, & Pacton, 2008). For example, in Icelandic the letter "þ" is most commonly the first letter of a word and words never begin with double consonants (e.g., hhestur). Additionally, children might use statistical information about the frequency of co-occurring words to predict what comes next in a sentence, leading to more efficient reading and correct use of sentence structure (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Spencer et al., 2014)

A study by Arciuli and Simpson (2012b) provided the first direct link between a capacity for SL and reading ability in typically developing children and adults. They found that performance on a temporal VSL task was significantly related to the ability to read aloud individually presented words of varying complexity. Those with a high capacity for VSL were more likely to be skilled readers than those with a low capacity. Importantly, these findings were not better explained by attentional factors, age or IQ, thus indicating a general learning mechanism independent of intelligence. More recently, Spencer et al. (2014) found that SL was related to skills critical to the development of literacy. In their study they compared the performance of typically developing children on tests of SL, visual and auditory, with skills in oral language, vocabulary knowledge and phonological processing. They found that SL accounted for a unique portion of the variance in these literacy-related skills. Importantly, they found that VSL accounted for a unique portion of the difference in the children's phonological processing skills. Children with poor phonological processing tended to have low capacity for VSL. Arciuli and Simpson (2012b) suggest that capacity for SL might explain why some people reach higher levels of reading proficiency than others, despite adequate schooling and similar reading experience. SL might thus explain the variable reading ability seen in the general population. Surprisingly, no inquiries have been made into the possibility that an unusually low capacity for SL could contribute to the reading difficulties found in dyslexics.

Research on neurobiological foundations of reading have revealed that a localized region of the fusiform gyrus, called the visual word form area (VWFA), is hypoactive in individuals with dyslexia (Richlan, Kronbichler, & Wimmer, 2011). The VWFA has been found to respond consistently more to words and letter strings in comparison to other visual objects (James, James, Jobard, Wong, & Gauthier, 2005). It is thought to play a major role in fast and accurate word recognition and correct mapping of sound to letters (Shaywitz & Shaywitz, 2008). Dehaene, Cohen, Sigman, and Vinckier (2005) have suggested that the

VWFA might integrate information regarding letters from lower levels of visual processing, such as from ITC neurons of the VVP, into a neural representation of words. While the VWFA does not discriminate between real words and pseudowords it does show more response selectivity to pseudowords than consonant strings (James et al., 2005). The difference between pseudowords and consonant strings is that pseudowords are made up of legal combinations of letters whereas consonant strings lack any such orthographic structure. The orthographic regularity of letter strings therefore appears to be the relevant variable for this area, but not lexical information (Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006). The sensitivity of the VWFA to orthographic structure indicates that it utilizes statistical information regarding legal co-occurrences of letters in its processing of word-like stimuli. Indeed, the VWFA is sensitive to the statistics of letter pairings and exhibits stronger responses to frequent letter-pairings than uncommon ones (Dehaene & Cohen, 2011). A study by Vinckier et al. (2007) showed that in addition to the VWFA being sensitive to the statistics of frequent letter pairings (bigrams), the VWFA is also tuned to the statistical regularities found in frequent 4-letter-strings (quadrigrams). In the study frequent letters, bigrams, and quadrigrams were compared to infrequent letters, bigrams and quadrigrams. The results showed that frequent letter-strings recruited the VWFA and other word-selective regions more in comparison to the infrequent letter-strings. Additionally, a gradient response was seen with activation in the VWFA increasing as the letter-strings formed closer statistical approximations to real words, with frequent quadrigrams showing the greatest response. This indicates that the VWFA is sensitive to the distributional statistics of letter groupings. Although frequent letters and word-like stimuli engage other areas of the fusiform gyrus and cortex of the VVP, the VWFA is the only area that shows such sensitivity to statistical regularities found in the observer´s native language (Dehaene & Cohen, 2011).

Interestingly, the VWFA has been found to be recruited in SL. In the Turk-Browne et al. (2009) study on the neurological basis of VSL they found that the VWFA is significantly recruited in VSL when observers are presented with statistically structured sequences, but not when observers are presented with random sequences containing no statistical structure. Using the temporal VSL paradigm observers were presented with two continuous sequences comprised of letter-like shapes. The structured sequence contained embedded triplets of co-occurring shapes whereas the random sequence contained shapes appearing in random order. Because both sequences contained novel letter-like shapes and assignment of shapes to

sequences was randomized, any difference in brain activity in response to the sequences must therefore have reflected sensitivity to the transitional probabilities of the structured sequence. The responses of the VWFA to letter-like shapes comes to no surprise. However, when comparing the responses for structured versus random blocks, the VWFA exhibited stronger responses to structured than random sequences. The VWFA therefore appears to be sensitive to statistical regularities of letter-like shapes presented over time. This opens up the possibility that VSL might be the learning mechanism that integrates input regarding letters from lower levels of visual processing into neural representation of words.

The sensitivity of the VWFA to statistical regularities is significant given that neurons in the VVP need to learn the properties of their receptive fields (Logothetis, Pauls, & Poggio, 1995; Peissig & Tarr, 2007). Reading is most probably a cultural development that causes brain circuits that originally evolved for object recognition to become tuned to recognize letters and words (Sigurdardottir et al., 2015). Although the VWFA selectively responds to words it is unlikely that the VWFA is restricted to that specific domain. In fact, the VWFA is also involved in the visual processing of faces (Nestor, Behrmann, & Plaut, 2013), tools (Dehaene et al., 2010) and meaningful symbols (Reinke, Fernandes, Schwindt, O'Craven, & Grady, 2008). Dehaene et al. (2010) have hypothesized that learning how to read recycles cortex in the VWFA so that it becomes increasingly more dedicated to the processing of words. In fact, with increased literacy VWFA activation for faces decreases while it increases for words (Dehaene et al., 2010). Most likely, the VWFA and related cortex of the fusiform gyrus is recycled because of its competence for extracting statistical configurations for object contours and because of its connectivity to the brains language areas (Dehaene & Cohen, 2011). This makes it ideal for the encoding of words. Dehaene et al. (2005) suggest that "perceptual learning mechanisms" ensure that only frequent and informative letters and letter combinations are selected to be encoded by dedicated neurons in word selective regions of the VVP. Dehaene et al. (2005) did not specify what these perceptual learning mechanisms might entail, but it is interesting that they should suggest that the recycling of cortex in VWFA might be governed by a process in which only frequent and informative letters and letter combinations are encoded. The recycling of the VWFA to words might therefore come about because of the regions capacity for SL. Importantly, the direct link between VSL and reading ability found in the Arciuli and Simpson (2012b) study and the direct link between VSL and literacy-related skills in the Spencer et al. (2014) study grants merit to such a view.

The hypoactivity of the VWFA of dyslexics might consequently reflect a failure to recycle cortex of the VWFA to the processing of words because of a deficit in VSL. Thus inhibiting the encoding of word-like stimuli based on statistical regularities found in written language. Such a deficit in SL could negatively impact the reading abilities of dyslexics in a number of ways, leading to impairments in (a) accurate mapping of letter to sound, (b) learning of informative and legal combinations of letters and (c) fluent reading because of inaccurate predictions of correct sentence structure. All are commonly identified impairments in dyslexia (Meyler & Breznitz, 2003; Norton et al., 2015).

The current study

The purpose of the study was to determine if dyslexics have a lower than usual capacity for VSL in comparison to typical readers. A growing body of research suggests that reading abilities and literacy-related skills vary in accordance with people´s capacity for VSL. It therefore follows that the reading difficulties found in dyslexics might in part be caused by impaired capacity for VSL. Evidence for this comes from neurobiological research demonstrating that the VWFA is recruited in temporal VSL. The VWFA which is primarily involved in the processing of words and letter strings has constantly been found to be hypoactive in dyslexics. This hypoactivity might reflect a failure to recycle the cortex of the VWFA to the processing of words and letter strings through the mediation of a perceptual SL mechanism. Therefore, the hypothesis of the current study was that dyslexics would perform more poorly on a test of temporal VSL than typical readers.

To our knowledge, no previous study has investigated whether a capacity for SL is directly related to dyslexia using the temporal VSL paradigm. In addition to the temporal VSL test presented in the current paper, further measures of intelligence, reading abilities and behavior were also adopted in the study. These are not included in the current thesis and can be found in corresponding thesis papers on the study.

Method

Participants

A total of 80 naive subjects participated in the study. Forty were diagnosed dyslexics (23 women) and 40 were typical readers (23 women). Seven participants were immediately resampled; four because button responses were not recorded, two because they fell asleep during the VSL test and one because later questioning revealed uncorrected vision. Subjects in the two groups were matched by age, gender and education. Thus for each dyslexic participant there was a typical reader of the same gender, age (±5 years) and educational background (three levels: finished high school, finished gymnasium or finished college at the undergraduate level). All participants had Icelandic as their native language and reported normal hearing and normal or corrected-to-normal vision. Furthermore, only participants who showed normal color vision on the 24-plate edition PseudoIsochromatic Plate (PIP) color vision test were included in the study.

The mean age for dyslexics was 27.3 years (age range: 19 to 60 years) and the mean age for typical readers was 26.9 (age range: 18 to 56 years). In each group, fifteen individuals had completed the first level of schooling, twenty had completed the second level of schooling and five had completed the third level.

All participants in the study were volunteers and were not rewarded for their participation. They were however offered to partake in a lottery. Four randomly selected participants received a gift card that could be used at a local shopping mall (value: 10.000kr-isk).

Test materials

Materials were the same for both groups and included a temporal VSL test with an additional shape recognition control test. Furthermore, participants answered a questionnaire measuring whether VSL was explicit in any way.

Development of a visual statistical learning test. For the purpose of the study two tests of VSL were developed. One was based on the temporal VSL paradigm and was the test used in the current study. The other was a related VSL experimental paradigm of spatial regularities and was not included in the final study. In this related paradigm, multiple shapes are presented at the same time. As in the temporal VSL paradigm these shapes form pairs of shapes that always co-occur and thus have a higher probability of co-occurring than other

possible shape pairings (Fiser & Aslin, 2001). A pilot study demonstrated that the spatial test yielded a smaller VSL effect than the temporal test. Because we were interested in comparing VSL of dyslexics and typical readers, the smaller effect of the spatial test might have proved insufficient to capture any possible difference between the groups. Therefore the temporal test of VSL was used in the final study.

Visual test of statistical learning. The test was modeled on previous research on the VSL of temporal transitional probabilities (Notably, Arciuli & Simpson, 2012b; Fiser & Aslin, 2002; Turk-Browne et al., 2009). The VSL test consisted of a familiarization phase with a cover task, a shape recognition control test and a two-interval forced-choice test.

The stimuli consisted of 48 novel shapes similar to those used in previous studies on VSL (e.g., Fiser & Aslin, 2001; Turk-Browne et al., 2009). These types of shapes have been shown to affect areas of the ventral visual cortex associated with VSL, including the VWFA (Turk-Browne et al., 2009). Fifteen shapes came from the Sabean alphabet (an extinct Semitic language) and 13 from the Ndjuka syllabary (a creole spoken in Suriname). In addition, 8 came from the Santali alphabet (a Munda language), 7 from the Agathodaimon font (a font based on mediaeval chemical symbols) and 5 from the Klingon alphabet (an artificial script created by fans of a science fiction TV show). Multiple alphabets were used to increase shape discriminability. Images of the shapes were generated using fonts of the respective alphabets downloaded at www.omniglot.com and www.fontpalace.com. The maximum height and width of each shape were scaled to be equal using The Image Processing Toolbox in Matlab.

Twelve of the 48 available shapes were randomly assigned without replacement to the familiarization phase and another twelve to the shape recognition control test. In the familiarization phase the twelve respective shapes were furthermore divided into 6 pairs. These six pairs were created by randomly selecting, without replacement, two shapes out of the twelve original ones until all shapes had been assigned to a pair. This created six unique shape pairs. These pairs are referred to here as base pairs and referenced as AB, CD, EF, GH, IJ, and KL.

The shapes assigned to each part of the VSL test and the order of their presentation was the same for each matched participant pair. Each dyslexic was thus presented with the same shapes in the same order as his typical reader counterpart in all subtasks of the test. This ensured that viewing specific stimuli did not influence the degree to which the matched pair differed in performance.

In all subtasks of the VSL test the appearance and size of the shapes were the same. Each shape appeared in black on a white background and subtended roughly 0.74° in height and 0.55° in width. Participants sat without head restraints approximately 62 cm from the computer monitor. The stimuli were presented on a 17 inch Cathode Ray Tube monitor (85 Hz refresh rate) using PsychoPy, an open-source application written in Python (Peirce, 2007).

Familiarization phase. The familiarization phase consisted of displaying the six base pairs in a continuous stream of sequential stimuli. One shape was shown at a time in isolation in the center of the display (Figure 1A). The two shapes that made up each pair always appeared consecutively in the same order during the familiarization phase (Figure 1B). In other words, when shape A was presented shape B always followed (e.g., ABEFABGHEFAB). Therefore, the initial member of a base pair always predicted the next member and the next stimuli after a pair was always an initial member of one of the six allowable base pairs.
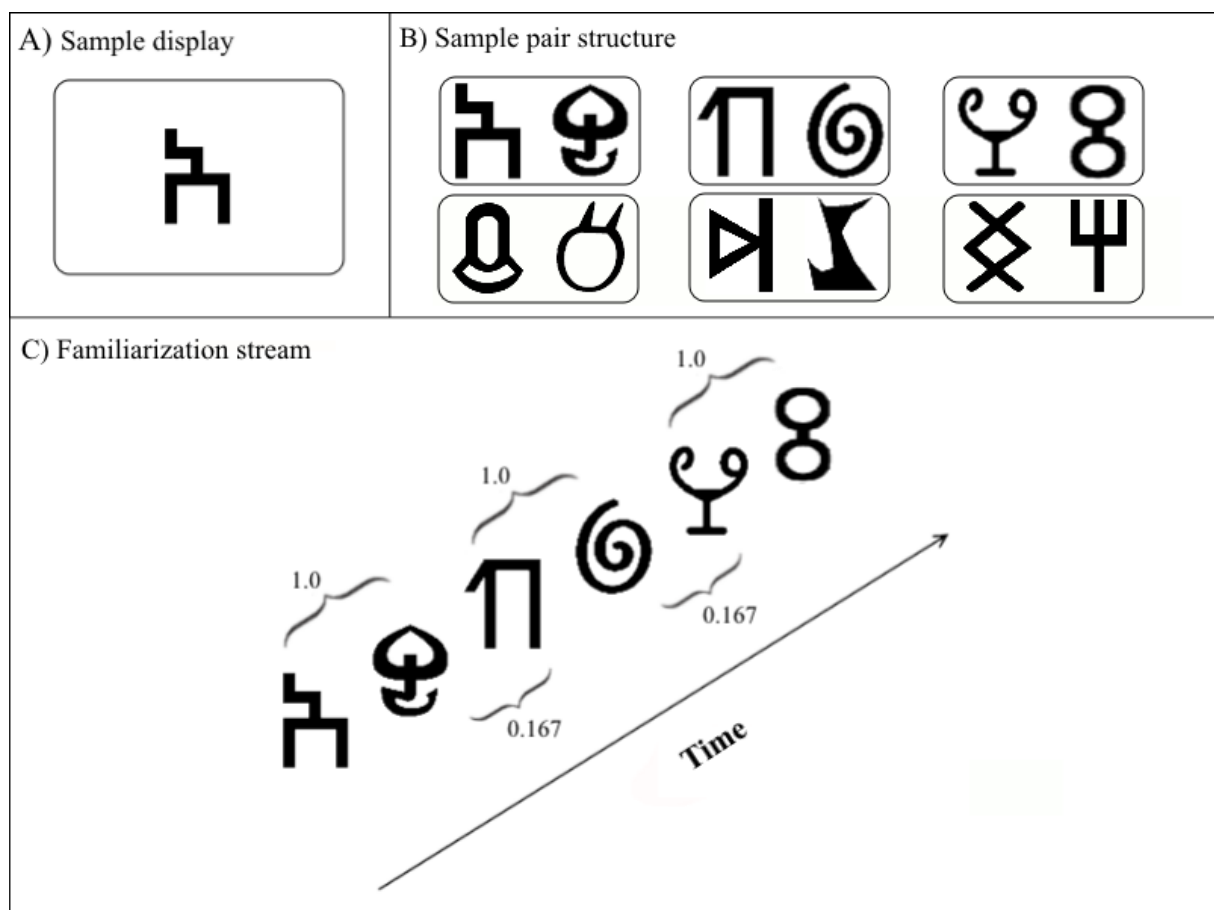

Figure 1. Schematic representation of stimuli and design. (A) Sample display of one shape. (B) Sample pair structure containing randomly selected shapes. (C) Depiction of the familiarization stream stimuli sequence and transitional probabilities defining pair boundaries.

There were no pauses between pairings and the underlying structure of the pairs was unknown to the participants. Thus only transitional probabilities defined boundaries between stimuli in the familiarization stream, constrained here to 1.0 within pairs and 0.167 between pairs (Figure 1C). This meant that if the shape C appeared there was a 100% probability that the next shape in line would be D. Also that given that the shape D had appeared there was a 16.7% chance that any of the six initial members of the base pairs would appear next. During the familiarization phase each shape was visible for 1500ms. The inter-stimulus interval (ISI) was 0 ms. Each base pair was displayed 72 times for a total of 864 trials. The order of the base pairs within the familiarization stream was randomized.

To provide a cover task individual shapes would occasionally jiggle and shift out of place. During these jiggle-trials, shapes would move from their center position in a random diagonal direction (top left, bottom left, top right and bottom right) for 0.2° and then veer back to their original position. The jiggle started at 650 ms into the trial and lasted for 200 ms. From the start of a jiggle participants had until 650 ms into the next trial to respond, before the possible appearance of another jiggle, giving the participants 1500 ms to respond. These jiggle-trials occurred randomly in one out of every six shape presentations for a total of 144 trials. The cover task ensured that participants were paying attention to the familiarization stream by requiring them to press a button every time a shape jiggled and served as a crude measure of attention. It also served to distract the participants from becoming aware of the underlying structure of the familiarization stream and the purpose of the study. Twelve practice trials introduced participants to the cover task using three additional shapes that were specially selected for the purpose and that did not appear in any other part of the statistical learning test.

Shape recognition control test. In the shape recognition control test the 12 shapes displayed in the familiarization phase (the base shapes) were pitted against 12 foil shapes that were not presented during familiarization and were therefore impossible for the participants to recognize. For each trial in the control test one base shape was displayed along with one foil shape. Both shapes were shown one at a time in isolation in the center of the display. Displayed for 1500 ms each with an ISI of 0 ms the two shapes were then followed by a 3000 ms empty white display. A 200 ms inter-trial interval separated trials. During the presentation of the last shape of each trial and for the time constrained duration of the empty white display, participants identified by pressing a button which of the two shapes had previously appeared in the familiarization stream. Each base shape was pitted against 4 random foil shapes selected from

the 12 possible foil shapes. The assignment of foils against base shapes was randomized with the single restriction that no one foil shape could appear along with the same base shape more than once. For a total of 48 randomized trials each base shape and each foil shape was displayed 4 times each. The order of the shapes within trials was counterbalanced with the base shape presented first in 2 out of 4 trials and the foils presented first in the remaining trials.

Each group was considered to have recognized the base shapes if significantly more than 50% (chance level) of the shapes were correctly identified as having been presented during the familiarization stream. The principal reason for implementing the shape recognition control test was to verify that, if the performance of the two groups on the VSL test differed significantly, it did not stem from dyslexics being poorer at recognizing the shapes than typical readers, which could reflect that any group difference was caused by a more general dysfunction in object perception.

Two-interval forced-choice test. For the two-interval forced-choice test (2IFCT) 6 foil pairs were created using the same 12 shapes displayed in the familiarization phase. For each of the original base pairs a corresponding foil pair was created utilizing the first shape in the base pair in addition to the second shape in another base pair. In creating the foils the second shape was selected randomly without replacement so that no single shape was assigned to a foil twice. Hence each shape would appear an equal number of times as both a member of a base pair and a foil pair. Shapes kept their respective position within base pairs when assigned to a foil pair. For example a shape that served as the first member in a base pair would also become the first member of the corresponding foil pair. The second shape of a base pair would likewise become the second member of a foil. This ordering created 6 unique foil pairs out of the original 12 shapes that had never appeared in the familiarization stream. For example, a foil created for the base pair AB would include the shape A in addition the second shape of another base pair selected randomly without replacement. If the second shape of the base pair GH was selected it would create the foil AH. Foils were therefore created using two shapes that had previously appeared in the familiarization stream but that had never appeared together sequentially. The within-pair transitional probability of the foil pairs was therefore equal to 0.

For each 2IFCT trial one base pair was displayed along with one foil pair. The shapes constituting each pair were displayed one at a time in isolation for 1500 ms each (ISI was 0 ms) with a 1000 ms gap separating the base pair from the foil pair. When both pairs had been presented an empty white display was shown for 3000 ms. A 200 ms inter-trial interval

separated trials. During the presentation of the last shape of each 2IFCT trial and for the time constrained duration of the white display participants decided by pressing a button which of the two pairs had appeared previously during the familiarization stream.

During the 2IFCT each base pair was pitted against each foil pair on two separate occasions. The order of base and foil pairs within trials was counterbalanced with base pairs presented first in half of the trials and the foil pairs presented first in the remaining trials. Across 72 randomized 2IFCT trials each base pair and every foil pair was presented an equal number of times for a total of 12 presentations each.

Chance performance was indicated by correctly identifying 50% of the base pairs presented in the 2IFCT. Conversely, VSL was said to have taken place if significantly more than 50% of the base pairs were correctly identified. On the grounds that transitional probabilities were the only factor defining between-pair-boundaries in the familiarization phase, a preference for base pairs over foils was taken as indicative evidence of VSL.

Implicitness of learning questionnaire. To assess the implicitness of learning in the VSL test a questionnaire was developed based on previous questions used by Turk-Browne et al. (2009). The questionnaire included six questions pertaining to the nature of the participants´ performance on the test and their awareness of the underlying structure of the pairs: (1) what they thought the statistical learning test was about, (2) what they did or thought of while engaged in the cover task, (3) whether they used any particular method of answering during the 2IFCT, (4) if they noticed any pattern or rule in the order of the shapes presented in the familiarization stream, (5) how good they thought their performance on the 2IFCT was and (6) if they had partaken in a similar study before. Answers were coded in an open-ended format.

Design

The design of the study was a matched pairs design. Each matched participant pair received the same experimental conditions in all parts of the study. The independent variable of the study was group membership which took two values: dyslexic or typical reader. The dependent variable of the jiggle cover task was the number of jiggles detected (hits). False alarms and jiggle-detection response times were also recorded. The dependent variable for the shape recognition control test was the percentage of base shapes correctly identified as having appeared previously during the familiarization phase. For the two-interval forced-choice test

the dependent variable was the percentage of base pairs correctly selected as having appeared previously during the familiarization phase.

Procedure

The study was approved by the Icelandic Science Review Board and the Icelandic Data Protection Authority. The study took place in a quiet and well lit room with only one participant partaking in the experiment at a time. After giving informed consent the visual test of SL and the shape recognition control test were administered. The experimenter then administered the Implicitness of Learning Questionnaire. Additionally, further measures of intelligence, reading abilities and behavior were implemented in the study. These are not included in the present thesis but can be found in corresponding theses on the study.

 Familiarization phase. Before beginning the familiarization phase the participant was positioned in front of the computer screen and the experimenter described this initial part of the statistical learning test. The experimenter read instruction aloud to the participants with matching instructions appearing on the computer display. As a cover task participants were instructed to monitor a continuous stream of shapes and to respond by pressing the space bar, without delay, when they noticed that any of the shapes jiggled. Additionally, as a dual cover task the participants were told that later on the researcher would ask them some questions pertaining to the appearance of the shapes. The reason for this dual cover task was that a pilot study indicated that participants tended to focus only on the movement of the shapes but not their appearance. Twelve practice trials were administered and the experimenter made sure that participants had understood the instructions before proceeding to the familiarization phase. Three breaks were administered intermittently with equal intervals during the familiarization phase. After a break, participants were instructed to press the enter key when they were ready to continue the experiment.

 Shape recognition control test. After the familiarization phase participants were asked without delay to identify which of the two shapes appearing on each trial they had seen previously during the familiarization phase. Like in the familiarization phase the experimenter read instructions to the participants aloud with matching instructions also appearing on the computer display. Participants were instructed to answer by pressing "1" or "2" on the keyboard indicating whether it was the shape appearing first in order or the second, respectively.

Two-interval forced-choice test. Immediately following the shape recognition control phase participants were informed that during the familiarization phase shapes had in fact appeared in pairs. They were told that if one shape of a pair had been presented, the other shape in the pair had also appeared, either preceding or following it. They were told that the test phase would measure the degree to which they had noticed these pairs. The experimenter read instructions to the participants aloud with matching instructions appearing on the computer display. During each 2IFCT trial they identified which of two presented pairs (a base pair and a foil) they had seen previously during the familiarization phase. Participants were instructed to answer by pressing "1" or "2" on the keyboard, indicating whether it was the first or second pair presented in order, respectively. There was one break halfway through the 2IFCT. Like in the familiarization phase participants were instructed to press the enter key when they were ready to continue the experiment.

Implicitness of learning questionnaire. Following the 2IFCT the experimenter read the questions on the Implicitness of Learning Questionnaire aloud and wrote down the participants´ answers. When all measures of the study had been administered each participant was debriefed and thanked for his participation in the study.

Statistical analyses

Analysis of the data revealed that two participants had misunderstood the instructions of the VSL test. One responded on most trials of the cover task and the second reported that he had responded contrary to instructions on the two-interval forced-choice test. This led to the removal of the corresponding pairs. All statistical tests were two-sided with an alpha level of 0.05. The results of the signal detection analysis were based a log-linear correction for extreme values (Stanislaw & Todorov, 1999). The results of a regression analysis for the cover task were based on correct responses. Response times smaller than 100 ms and three standard deviations from the mean were excluded in the regression analysis. This led to the removal of 224 responses, or 2.1% out of a total of 10482 correct responses. The results of repeated measures ANOVAs were Greenhouse-Geisser corrected when Mauchly´s test of sphericity indicated deviations from sphericity. Effect sizes were estimated using eta-squared ($\eta2$), Cohen´s d and the squared semi-partial coefficient (sr^2).

Results and discussion

Familiarization phase and cover task

A signal detection analysis revealed that both typical readers and dyslexics completed the jiggle-detection cover task during the familiarization phase with few errors. Dyslexics detected an average of 93.9% of the jiggles ($SD = 5.7\%$) and committed 0 to 31 false alarms. Typical readers detected an average of 96.8% of the jiggles ($SD = 4.1\%$) and committed 0 to 15 false alarms. These results show that participants in both groups were attentive to the familiarization stream.

However, dyslexics detected on average 2.9% fewer jiggles than typical readers. A matched pairs one-factor repeated measures ANOVA showed a main effect for the performance of the two groups, $F(1, 37) = 7.66$, $p = 0.009$, 95% CI [-5.1%, -0.8%], $\eta2 = 0.17$, with dyslexics detecting significantly fewer jiggles than typical readers. The signal detection analysis revealed that dyslexics had on average a discriminability index of $d' = 4.43$ ($SD = 0.69$) and a response criterion of $c = -0.84$ ($SD = 0.25$). Meanwhile, typical readers had on average a discriminability index of $d' = 4.89$ ($SD = 0.63$) and a response criterion of $c = -0.1$ ($SD = 0.22$). The discriminability index d' differed significantly between groups with dyslexics showing a smaller discriminability index: paired-samples t test, $t(37) = 3.15$, $p = 0.003$, 95% CI [-0.75, -0.16], $d = 0.70$. This indicates that dyslexics were not as good at discriminating the jiggle-trials from non-jiggle trials as typical readers. This is evidence that dyslexics were not as attentive to the familiarization stream as typical readers. The response criterion c also differed significantly between the groups with dyslexics showing a larger response criterion: paired-samples t test, $t(37) = -2.73$, $p = 0.01$, 95% CI [0.04, 0.26], $d = 0.63$. This indicates that dyslexics adopted a more conservative response strategy and were more careful in their answers than typical readers.

Although not the purpose of the cover task, we wanted to know whether the first member of a pair came to predict the second member as a consequence of VSL. It is possible that the first shape in pair led to anticipatory processing of the second shape, leading to quicker detection of jiggles in the second member as the familiarization stream progressed. The cover task would thus provide an additional measure of learning.

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As depicted in figure 2, the mean response time (RT) of typical readers was the same for jiggles in both members for the first 100 familiarization trials. As the stream progressed their RTs for both members became faster. Interestingly, their RTs for jiggles in the second shapes became somewhat faster in comparison. This might indicate that VSL of the pair structure led to anticipatory processing of the second member of a pair. However, as indicated by the relatively large confidence intervals there is much uncertainty as to how large this difference was within trial ranges.
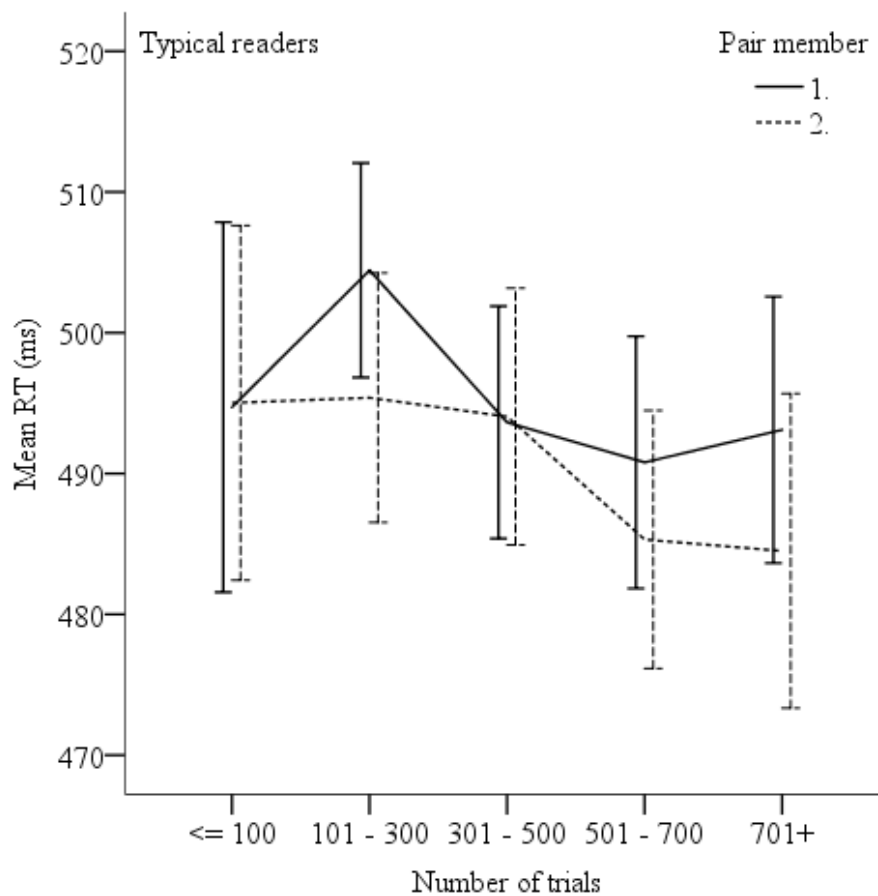

Figure 2. Mean response time (RT) of typical readers for jiggle detection by pair member and number of trials. Shape 1 and 2 correspond to the first and second members of pairs, respectively. Error bars mark the 95% confidence interval of each trial range.

As depicted in figure 3, the RTs of dyslexics to jiggles in the first and second members of pairs showed a different pattern. Interestingly, dyslexics showed an inverted-U pattern of responding. Their RTs for both pair members grew longer for the first half of the stream and then steadily grew faster again for the latter half. They never surpassed their initial RTs for jiggles in both shapes, although RTs for the two shapes appear to have differed markedly around the 700th trial.
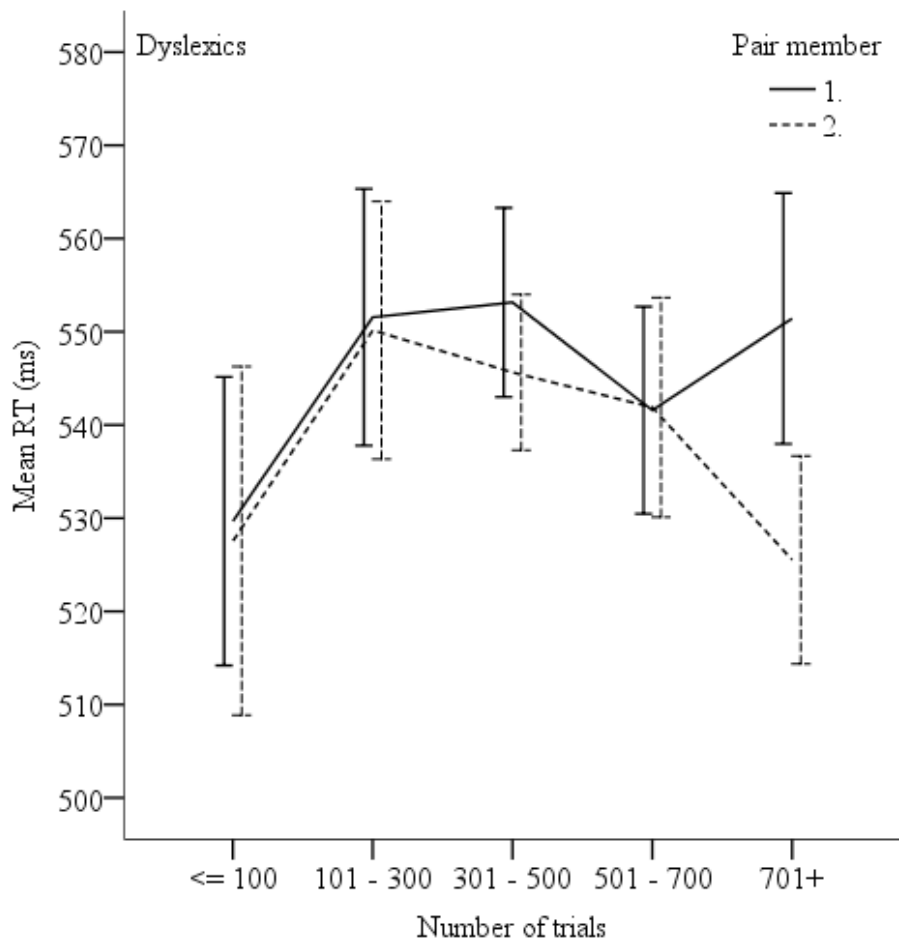

Figure 3. Mean response time (RT) of dyslexics for jiggle detection by pair member and number of trials. Shape 1 and 2 correspond to the first and second member of pairs, respectively. Error bars mark the 95% confidence interval of each trial range.

A linear regression analysis was conducted to assess whether the change in RTs to jiggles differed by group and pair member as the familiarization stream progressed. Table 1 demonstrates that number of trials significantly predicted RTs of typical readers for jiggles in the second member of a pair, but not for the first member of a pair. Number of trials did not predict RTs of dyslexics for jiggles in either member. As the familiarization stream progressed, typical readers therefore responded faster to jiggles in the second member of a pair whereas dyslexics showed no noticeable change in RTs for jiggles in either shape. This could mean that typical readers responded faster to jiggles in the second member of a pair as consequence of VSL.

Table 1. *Summary of Regression Analysis for Number of Trials Predicting Response Time (ms) by Pair Member and Group. (N = 38)*

Group	Shape	Constant	*B*	*SE(B)*	Beta
Typical readers	1	502	-0.014	0.008	-0.034
	2	499	-0.019*	0.009	-0.041
Dyslexics	1	545	0.004	0.012	0.007
	2	547	0.011	0.011	-0.011

Note. Shape corresponds to the first and second members of pairs.

* $p = 0.036$.

However, for typical readers the standardized beta coefficient (β) of the first members did not differ distinguishably from the standardized beta coefficient of the second members: paired-samples *t* test, $t(37) = 1.11$, $p = 0.28$, 95% CI [-0.03, 0.09]. The same applied to dyslexics: paired-samples *t* test, $t(37) = 1.51$, $p = 0.14$, 95% CI [-0.01, 0.09]. The slopes of the first and second members of pairs were therefore indistinguishable in both groups. This indicates that the RT to jiggles in both groups did not come to differ by pair member as the familiarization stream progressed. Thus, the appearance of the first shape in a pair did not lead to more efficient processing of a jiggle in the second shape as a consequence of VSL. The cover task did therefore not provide an additional measure of VSL in the current study.

Shape recognition control test

Performance on the shape recognition control test was in general very good. Our measure of adequate shape recognition was the percentage of test trials in which the base shapes were correctly identified as having appeared in the familiarization stream (chance level recognition = 50%). On average dyslexics correctly identified 95.9% ($SD = 6.2\%$) of the base shapes when pitted against foils, with a range of 64.6% to 100%. Their recognition of the base shapes was significantly greater than chance level: one-sample t test, $t(37) = 45.5$, $p < 0.001$, 95% CI [43.9%, 47.9%]. In comparison, typical readers correctly identified on average 98.2% ($SD = 3.6\%$) of the base shapes when pitted against foils, with a range of 79.2% to 100%. Their performance was also significantly greater than chance level: one-sample t test, $t(37) = 82$, $p < 0.001$, 95% CI [47%, 49.3%]. Therefore, both groups adequately recognized the majority of the shapes that appeared during the familiarization stream. Dyslexics correctly identified 11.5 base shapes on average whereas typical readers correctly identified 11.8 base shapes on average. A comparison of the difference between the performance of the groups using a one-factor repeated measures ANOVA showed a main effect for matched pairs, with dyslexics recognizing significantly fewer base shapes than typical readers, $F(1, 37) = 4.34$, $p = 0.044$, 95% CI [-4.4%, -0.1%], $\eta2 = 0.11$. It therefore appears that dyslexics were not as good as typical readers at recognizing the shapes presented.

Two-interval forced-choice test

In the 2IFCT our measure of VSL was the percentage of test trials in which the base pairs were correctly chosen as having appeared previously during the familiarzation stream (chance level = 50%). As depicted in figure 4, both dyslexics and typical readers reliably disthinguished between base pairs and foil pairs. On average dyslexics correctly chose 67% ($SD = 19.5\%$) of the base pairs previously presented, with a range of 30.6% to 100%. Their performance was significantly greater than chance level: one-sample t test, $t(37) = 5.38$, $p < 0.001$, 95% CI [10.6%, 23.4%]. In comparison, typical readers correctly chose on average 77.5% ($SD = 18.4\%$) of the base pairs previously presented, with a range of 27.8% to 98.6%. The performance of typical readers on the 2IFCT was also significantly greater than chance level: one-sample t test, $t(37) = 9.2$, $p < 0.001$, 95% CI [21.4%, 33.5%]. These results indicate that both dyslexics and typical readers were able to learn the statistical regularities present in the familiarization stream.

Importantly, dyslexics performed on average 10.5% poorer on the 2IFCT than typical readers. A comparison of the difference using a one-factor repeated measures ANOVA demonstrated a main effect for matched pairs, with dyslexics showing significantly weaker VSL than typical readers, $F(1, 37) = 8.12$, $p = 0.007$, 95% CI [-17.9%, -3%], $\eta2 = 0.18$. This indicates that dyslexics had a lower capacity for learning the statistical regularities of the familiarization stream than typical readers.
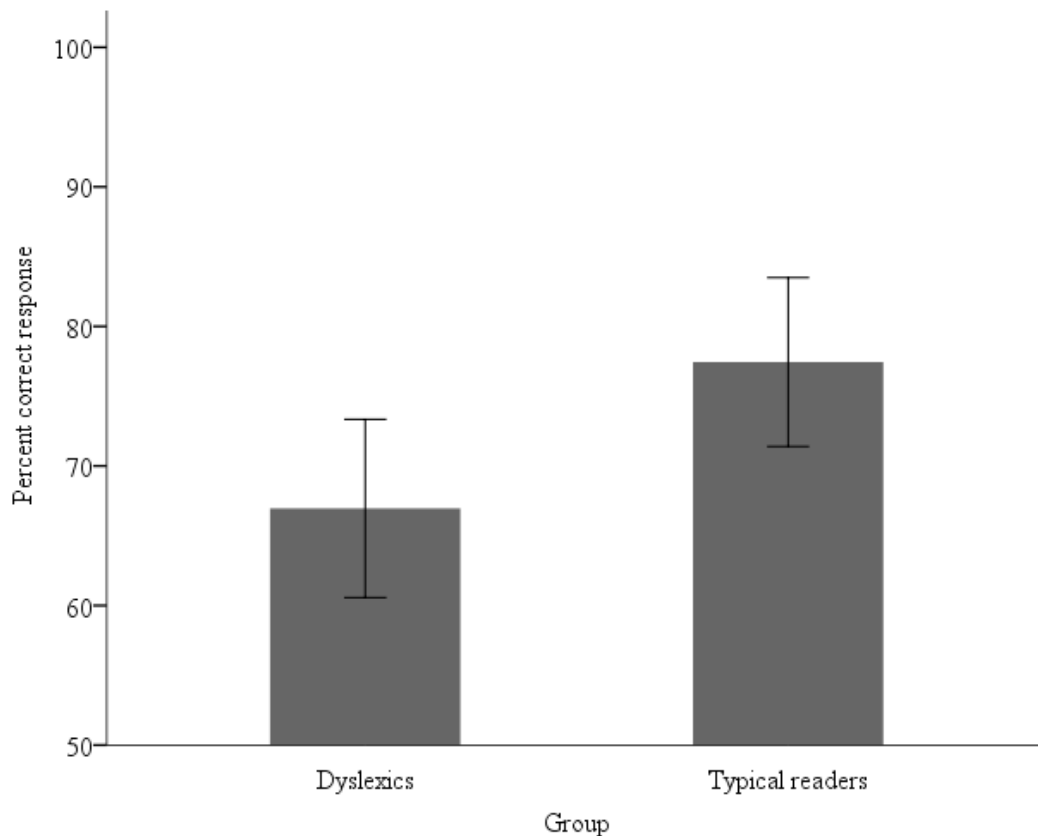

Figure 4. Mean performance of dyslexics and typical readers on the two-interval forced-choiced test. The y-axis is truncated below 50%, which is chance level performance for both groups. Error bars mark the 95% condifence intervals of each group.

To assess whether this effect would hold up, while controlling for the poorer performance of dyslexics on the cover task (*d′* – discrimination index) and shape recognition control test (percent correct), a dummy coded regression analysis was conducted (1 = dyslexics, 0 = typical readers). Over all the regression model predicted 7% (adjusted) of the performance of the groups on the 2IFCT. Dyslexia was still a predictive factor of the performance on the 2IFCT even while controlling for performance on the cover task and shape recognition control test.

The differential intercept coefficient (β) was equal to -9.3% and was marginally significant, $t(72) = -2$, $p = 0.049$, 95% CI [-18.7%, -2.2%]. Therefore, dyslexia predicted a 9.3% decrease in performance on the 2IFCT even when performance on the cover task and shape recognition control test was held constant. In addition, the semi-partial correlation (sr) between dyslexia and performance on the 2IFCT demonstrated that dyslexia was negatively correlated with performance on the 2IFCT, $sr(72) = -0.22$, $p = 0.049$, $sr^2 = 0.05$. Thus, dyslexia accounted for 5% of the variance in the performance on the 2IFCT when accounting for performance on the cover task and the shape recognition control test.

Implicitness of learning questionnaire

The majority of participants reported in response to question (1) that they thought the study concerned attention or memory ($N = 56$). Only 5 participants reported that they thought it concerned the perception of shape pairs. Others reported that they thought that the study was on shape perception ($N = 5$), on reflexes ($N = 3$), on perception of movement ($N = 2$) on brain functioning ($N = 1$) or on patience ($N = 1$) Four percent claimed to have no idea of what the study concerned. Thus, only 5 participants suspected the true purpose of the study. However, the questionnaire was administered after the participants had been notified of the existence of the shapes so this might be expected.

For question (2) what the participants did or thought of while engaged in the cover task, responses were coded into four categories: 1. Named the shapes or thought of their resemblance to other objects ($N = 35$), 2. Simply watched the shapes and responded when they jiggled ($N = 33$), 3. Looked for a pattern or rule in the sequence ($N = 6$) and 4. Counted the shapes ($N = 2$). Six participants therefore claimed to have looked for a pattern or rule in the sequence. Of which there were three dyslexics and three typical readers.

For question (3) whether the participants used any particular method of answering during the 2IFCT, responses were coded into five categories: 1. Used no particular method ($N = 29$), 2. Tried to be consistent in their answers when choosing between the base and foil pairs ($N = 17$), 3. Tried to think back to the familiarization phase ($N = 11$), 4. Tried to use the names they had give the individual shapes ($N = 13$) and 5. Followed their gut feeling ($N = 6$). Therefore, the majority used no particular method in choosing between base and foil pairs or tried to be consistent in their answers.

For question (4) if the participants had noticed any pattern or rule in the order of the shapes presented in the familiarization stream, responses were coded into four categories: 1. Did not notice any pattern or rule in the order of the sequence ($N = 45$), 2. Noticed a pattern or realized that shapes were presented in pairs but could not describe them ($N = 12$), 3. Noticed one base pair ($N = 6$) and 4. Noticed two or more pairs ($N = 13$). Therefore, only 6 participants noticed one shape pair (4 dyslexics, 2 typical readers) and only 13 reported to have noticed two shape pairs or more (5 dyslexics, 8 typical readers). However, when asked no participant could report all shape pairs. Nonetheless, the performance of both groups on the 2IFCT indicates robuts statistical learning. In addition, these questions were administered after the participants had been informed of the existance of the shape pairs, so these numbers are likely to be an overestimation of participants true awareness of the pair structure. This is strong evidence that learning during the familiarization phase was indeed implicit for both groups and that performance on the 2IFCT was not better explained by explicit awareness of the shape pairs. The difference in VSL found between dyslexics and typical readers was therefore unlikely to be caused by one group being more explicitly aware of the pair structure than the other.

Further evidence for the implicitness of learning during the VSL test came from the participants response to question (5) regarding how good they thought their performance on the 2IFCT was. On average dyslexics estimated that they correctly chose base pairs over foils 57.6% of the times. Almost ten percent lower than their actual average of 67%. Typical readers estimated their performance even worse with an average of 46%. Over thirty percent worse than their actual average of 77.5%. Thus participants in both groups underestimated their performance, which indicates that participants implicitly recognized more shape pairs than they were consciously aware of. In response to question (6) all participants reported to have never participated in a similar study before.

General discussion

The current study indicates that dyslexics have an impaired capacity for VSL. The hypothesis that dyslexics would perform more poorly on a test of temporal VSL than typical readers was therefore supported. In the study, both dyslexics and typical readers demonstrated learning of the statistical regularities found in a temporal stream of letter-like shapes. Both dyslexics and typical readers selected the base pairs hidden in the familiarization stream as having appeared in the familiarization stream significantly more often than foil pairs – that contained the same shapes as the base pairs but that were never presented together sequentially. Since transitional probabilities were the only factor indicating the existence of the base pairs this preference for base pairs over foils shows that both groups were sensitive to the statistical structure of the familiarization stream. These results are consistent with previous studies demonstrating the brain´s capacity for extracting transitional probabilities of how features and objects co-occur over time (Fiser & Aslin, 2002; Turk-Browne et al., 2005; Turk-Browne & Scholl, 2009).

Although both groups demonstrated robust temporal VSL in the study, importantly, dyslexics showed significantly weaker learning. Dyslexics selected significantly fewer base pairs as having appeared in the familiarization stream as compared to typical readers. This shows that dyslexics were not as sensitive to the pair structure of the familiarization stream. They more often missed what was hidden in plain sight. However, on the cover task dyslexics detected significantly fewer jiggles than typical readers which indicated that they were not as attentive to the familiarization stream. In addition, on the shape recognition control test dyslexics recognized fewer of the shapes presented in the familiarization stream than typical readers. Therefore the difference between dyslexics and typical readers on the temporal VSL test might have been better explained by dyslexics being less attentive and poorer at recognizing the shapes. But these differences were small and both groups were adequately attentive to the familiarization stream and recognized the majority of the shapes presented. When controlling for these factors in the study, dyslexia was still a significant predictor of poorer performance on the VSL test. It can therefore be concluded that dyslexics have a lower than usual capacity for temporal VSL as compared to typical readers and that this difference is not better explained by attentional factors or poorer recognition of the shapes presented. The results therefore indicate that dyslexics are generally poorer at learning how objects in the environment co-occur over time through an implicit VSL mechanism.

In addition to the main measure of VSL in the study, the 2IFCT, a response time analysis of the jiggle cover task was conducted. Although not the purpose of the cover task, we wanted to see if VSL would lead to speedier responses to jiggles in the second member of base pairs as the familiarization stream progressed. But this analysis did not provide an addition measure of learning. The first member of a pair did not come to predict the second member of a pair as a consequence of VSL. The cover task was however ill suited for this purpose since participants were not instructed to answer as fast as they could and may therefore not have revealed the VSL that took place during the familiarization phase.

Following the 2IFCT the Implicitness of Learning Questionnaire was administered to assess whether learning during the familiarization phase was explicit to any degree. In response to the questionnaire no single dyslexic or typical reader reported full awareness of the pair structure and the majority reported to have no awareness of the shape pairs whatsoever. This shows that dyslexics´ and typical readers´ learning during the temporal VSL test was both implicit and without intent. These results are consistent with previous studies demonstrating the implicit nature of VSL (Turk-Browne et al., 2009). It also shows that the poorer performance of dyslexics on the temporal VSL test was not caused by one group being more explicitly aware of the pair structure than the other.

The findings of the current study are consistent with a growing body of research indicating that reading abilities and literacy-related skills, such as phonological processing, vary in accordance with people´s capacity for VSL (Arciuli & Simpson, 2012b; Arciuli & von Koss Torkildsen, 2012; Baker et al., 2004; Spencer et al., 2014). Dyslexics demonstrated distinguishably lower capacity for VSL in comparison to typical readers. The reading difficulties seen in dyslexia might therefore reflect a deficient capacity for detecting statistical regularities in written language. Such a deficit would explain the difficulties dyslexics have with accurate mappings of letters to sounds, learning legal combinations of letters and sounds and accurate prediction of correct sentence structure (Meyler & Breznitz, 2003; Norton et al., 2015). All are abilities that VSL is thought to play a major role in (Arciuli & Simpson, 2012b; Arciuli & von Koss Torkildsen, 2012; Conway et al., 2010; Deacon et al., 2008; Spencer et al., 2014).

The results of the study are furthermore consistent with neurobiological research that has shown that the VWFA, a region of the ventral cortex important in word processing, is hypoactive in individuals with developmental dyslexia (Richlan et al., 2011). This brain region

has recently been found to be recruited in a task of temporal VSL using letter-like shapes as stimuli (Turk-Browne et al., 2009). The current study therefore opens up the possibility that the hypoactivity seen in the VWFA of dyslexics might reflect a deficit in a perceptual VSL mechanism. Written language is most probably a cultural development that causes brain circuits that originally evolved for object recognition to become tuned to recognize letters and words (Sigurdardottir et al., 2015). Dehaene et al. (2005) have suggested that "perceptual learning mechanisms" ensure that only frequent and informative letters and letter combinations are selected to be encoded by dedicated neurons in word selective regions of the brain. They did not specify what these mechanism might ential but the direct link between VSL and reading abilities as well as the direct link between VSL and literacy-related skills suggest that the recycling of the VWFA to words might be achieved through VSL. It is therefore reasonable to infer from the results of our study that the hypoactivity of the VWFA in dyslexics might reflect a failure to recycle the cortex of the VWFA to the processing of words and letter strings through the mediation of a perceptual VSL mechanism.

These findings are important since they mean that tests of VSL could be adopted as screening measures for developmental dyslexia at a much younger age than previous measures have allowed. VSL has in fact been found to emerge early in infancy (Bulf et al., 2011; Kirkham et al., 2002). Tests of VSL only require that participants understand the instructions given and be capable of attending to the stimuli presented. A relatively simple version of the temporal VSL paradigm could therefore be administered to pre-school aged children before learning to read. Such screening for a VSL deficit could possibly lead to speedier intervention in high risk children for dyslexia and the adequate aid before any noticeable reading impairments emerge possibly allowing the children to reach a higher level of reading mastery and possibly allowing them to keep up with their classmates. Such interventions could take the form of explicit teaching and increased exposure of dyslexic children to low-frequency regularities in written language that they might have more difficulty in acquiring themselves. Future studies could look to devise such a screening measure and see whether the findings of the current study can be replicated in a sample of pre-school aged children.

The current study was limited in three ways. The first limitation was that multiple shapes were randomly assigned to constitute the base and foil pairs for each matched participant pair in the VSL test. Although the use of multiple shapes increased shape discriminability it might have also increased the variability seen between the matched pairs. Such variability might have

come about because some shapes assigned to each matched pair were more gestalt grouping friendly than others. A study by Baker et al. (2004) demonstrated that the connectedness of paired shapes could influence the degree to which VSL takes place. It is therefore possible that similar grouping principals, such as the shapes degree of similarity, might have influenced the results of the current study. Any increase in variability in the matched pairs´ performance might have masked a clearer difference between dyslexics and typical readers. The second limitation of the study was that the shape recognition control test was administered before the 2IFCT. Because each base shape was presented in isolation, detached from their respective pair member, it is possible that it undermined to some extent the learning that took place during the familiarization phase. Furthermore, because each shape was presented with a foil shape during the shape recognition control test this could have caused new temporal relations that undermined previous learning of the base pairs. The poorer performance of dyslexics on the 2IFCT might thus reflect that they were more interrupted by the shape recognition control test than typical readers were. If so this could reflect a deficit in the consolidation of VSL rather than a deficit in detecting regularities as this study indicates. The third limitation of the study was that the questionnaire used to measure the implicitness of learning during the familiarization phase did not require the participants to describe the base pairs they recalled. Therefore there was no way to validate the degree to which their answers corresponded with the actual pairs presented. The questionnaire may therefore have overestimated the degree of explicit awareness in the VSL test.

Future studies could set out to replicate the findings presented here with refinements of these limitations. Another future direction would be to replicate the study presented here with a spatial VSL paradigm. In this paradigm, multiple shapes are presented at the same time. As in the temporal VSL paradigm these shapes form pairs of shapes that always co-occur and thus have a higher probability of appearing together than other shape pairings (Fiser & Aslin, 2001). Reading involves the simultaneous processing of multiple letters and words. A spatial VSL test would more precisely approximate the task of reading wherein multiple letters and words are processes at the same time. Future studies might also assess whether dyslexics and typical readers differ on the ability to transfer learning of regularities across space and time. VSL has been found to transfer between different contexts of learning. Learning of temporal regularities can transfer over to spatial regularities and vice versa (Turk-Browne & Scholl, 2009). As we read our eyes are constantly moving. Temporal regularities might emerge in reading because

our eyes gather information from specific points in space distributed over time. Spatial regularities might emerge as we simultaneously process multiple letters and words at specific points in time. Future studies could assess whether dyslexics are impaired in the transfer of VSL across temporal and spatial contexts. Such studies would provide a clearer picture of the nature of the VSL deficit in dyslexia found in the current study and reading more generally.

Conclusion

A growing body of research indicates that accurate reading might reflect an ability to detect statistical regularities in written language. In support of this are studies demonstrating that reading abilities and literacy-related skills vary in accordance with people´s capacity for VSL. The findings of the current study indicate that the reading difficulties seen in dyslexia could in part be caused by a VSL deficit. Dyslexics demonstrated significantly weaker VSL about temporal regularities in comparison to typical readers, even when accounting for attentional factors and poorer recognition of the shapes presented. The reading difficulties seen in dyslexia might therefore reflect an impaired capacity for detecting statistical regularities in written language. These findings open up the possiblity that the hypoactivity seen in the visual word form area of dyslexics might reflect a failure to recycle the brain region to the processing of words through the mediation of a perceptual statistical learning mechanism.

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