The role of visual processing in reading ability and disability:

Can dyslexia be partially traced to a deficit in statistical learning?

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HÁSKÓLI ÍSLANDS

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There is growing evidence that statistical learning, the ability to detect statistical regularities in the environment, underlies reading. Recent studies suggest that a higher statistical learning ability is related to a higher reading ability in the general population. The objective of the current study was to determine if dyslexics show a deficit in statistical learning. We compared the performance of 39 adult dyslexics (M = 27.2 years) and 39 matched typical readers (M = 26.6 years) on a well-established statistical learning test. Dyslexic participants showed significantly poorer performance on the statistical learning test compared to typical readers. These results held after controlling for participants' nonverbal intelligence, ADHD, object recognition abilities and handedness. Our results indicate that dyslexia can be partially traced to a deficit in statistical learning. It is therefore possible that dyslexia represents a general impairment in statistical learning.

Preface

This BSc thesis was written under the guidance of Dr. Heiða María Sigurðardóttir and Dr. Árni Kristjánsson. We are honored to have worked with such excellent scientists and thankful for their great mentoring and assistance. They have played a large role in stimulating our profound interest in the field of cognitive neuroscience. In addition, we want to thank Dr. Daníel Þór Ólason for providing invaluable help and advice and for always taking time to answer our questions. This thesis would not be half as good without you all.

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Object recognition and the visual word form area

Recognizing a cup of coffee, your friend at a party, or the words on this page does not seem very challenging. Humans are able to recognize tens of thousands of meaningful objects, and this ability is of fundamental importance for their functioning in daily life (Clarke, Taylor, & Tyler, 2011). Recognizing this variety of stimuli is accomplished by systematically categorizing visual objects based on groupings of features in the environment (Logothetis & Sheinberg, 1996). These categories do not simply reflect linguistic concepts but are based on perception. That is, our ability to categorize objects depends on how we perceive them, and is therefore perceptual instead of being the product of language development (Logothetis & Sheinberg, 1996). Research suggests that object categories develop independently of language and prior knowledge, and are based on the same principles as object recognition in other animals (Logothetis & Sheinberg, 1996). Environmental structure is therefore more important for categorization than language, because we learn which objects are more likely to go together in the visual environment than others (Logothetis & Sheinberg, 1996). For instance, features such as “tails” and “whiskers” often co-occur, while features such as “tails” and “glasses” generally do not.

Visual object recognition is a fast and effortless process, even when we encounter objects under different light conditions and from different viewpoints, and when we can only see parts of whole objects (Logothetis & Sheinberg, 1996). The apparent ease with which we identify this multitude of visual objects conceals the extremely challenging computational task this process involves. In a split second we recognize and classify objects from among an enormous amount of possibilities without even noticing (DiCarlo, Zoccolan, & Rust, 2012). Further, even the same object never provides the same information to the sensory organs on two different occasions (Soto & Wasserman, 2010). This computational complexity is reflected in the fact that up to 30% of the human neocortex is largely or exclusively involved in visual processing (Weiner, Nelson, & Mizumori, 2012).

The key brain circuits underlying visual object recognition are situated in the ventral visual stream, a set of cortical areas arranged along the occipital and temporal lobes (DiCarlo et al., 2012). Specific brain regions in the ventral visual stream respond selectively to certain object categories (Amit, Mehoudar, Trope, & Yovel, 2012). Such selective neural response has been reported for faces, places, body parts, and words or letter strings (Amit et al., 2012). Evidence for this category specificity comes from studies showing dissociations of spared and impaired performance in the recognition of different classes of objects (Ward, 2015). For instance, many studies have described patients with damage in the occipitotemporal region of the right hemisphere who have lost the ability to recognize faces but not other objects categories (Kanwisher, McDermott, & Chun, 1997). However, there has been substantial debate among researchers concerning category specificity, since it is possible that different object categories require different kinds of processing, and that such differences are relative rather than absolute (Ward, 2015).

The visual word form area (VWFA) in the left posterior fusiform gyrus (Woodhead, Wise, Sereno, & Leech, 2011) has received much attention among researchers. The VWFA is considered to be involved in reading (e.g., Cohen & Dehaene, 2002; Cohen & Dehaene, 2004; Dehaene & Cohen, 2011; Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). The VWFA shows greater activity when literate people are presented with letter strings compared to visual control stimuli such as checkerboards (Cohen & Dehaene, 2004), supporting this area's role in reading and visual word processing (Sigurdardottir et al., 2015). In addition, research suggests that the VWFA processes input that is specific to reading and cannot be reduced to general visual recognition (Dehaene & Cohen, 2011). Dehaene and Cohen (2011) found that when observers were presented with written sentences, activation in the VWFA increased in proportion to reading performance. Likewise, a lesion of the VWFA or its surrounding networks causes loss of the ability to process letter strings efficiently, causing a severe reading impairment known as pure alexia. However, people with pure alexia are also impaired at tasks that depend on the perception of non-word visual objects, indicating that this reading impairment is not completely pure (Dehaene & Cohen, 2011; Sigurdardottir et al., 2015).

The VWFA's response is prelexical (Dehaene & Cohen, 2011), meaning that information is assembled directly from the printed letters independent of word meanings (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; Frost, 1995). This suggests that the VWFA is limited to the extraction of abstract letter strings and is not involved in proper visual word recognition (Kronbichler et al., 2004). Indeed, research suggests that the VWFA's response to visual words has a short latency of 150-200 milliseconds (Dehaene et al., 2002). These short latency potentials seem to be insensitive to word type, since the VWFA responds equally to pseudo-words and regular words. This indicates an early, automatic stage of category-specific processing (Puce, Allison, Asgari, Gore, & McCarthy, 1996). The VWFA's response is also strictly visual, with no activity above baseline to spoken words (Dehaene & Cohen, 2011). Since research suggests that the VWFA plays an important role in reading, this strictly visual response supports the idea that the process of reading depends not only on language comprehension but also to a large extent on visual object recognition. Just as in the case of other kinds of object recognition, during reading we must recognize the input to understand words' meaning (Cohen & Dehaene, 2002). Most modern theories of reading suggest that word recognition is based on the analysis of letters, independent of the letters' surface properties such as case and location (Rastle, 2007). Indeed, the VWFA's response to letters is invariant for both the letters' location and case (Dehaene & Cohen, 2011). This enables skilled readers to recognize words rapidly, even when the words appear in unfamiliar surface contexts (Rastle, 2007). Research also suggests that the VWFA is sensitive to familiar letter sequences, which indicates that sensory experience leads to a perceptual tuning in the VWFA to given letter probabilities (Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006).

Visual word recognition seems to be more than the sum of its parts, since patterns across letters are very important for their recognition. For instance, detecting a single letter is easier when it is presented in the context of a word than when presented in isolation (Ward, 2015) or in a nonword (Falikman, 2011). For example, when presented with a word or a nonword string and asked to name one of the letters in that string making a two-alternative forced choice, such as choosing between the letters R and N, people are usually more efficient in this task when the letter is presented in the word "bird" than when it is presented in the nonword "bqrd" (Falikman, 2011). Further, visual word recognition is not strongly affected by word length, which suggests that during efficient reading, letters are processed in parallel rather than serially one by one (Ward, 2015). Supporting this, activity in the VWFA is unaffected by word length (Ward, 2015). This is different from spoken word recognition where information is revealed gradually and must be processed over time (Ward, 2015). This parallel processing of letters suggests that top-down information, such as stored knowledge of the structure of known words, plays a role in visual word recognition (Ward, 2015).

Dyslexia

The invention of writing is very recent. Literacy first emerged around 5,000 years ago and is by no means universal (Dehaene & Cohen, 2011; Ward, 2015). It is therefore highly unlikely that a mechanism dedicated to reading has evolved in the human brain. Some researchers propose that learning to read involves ‘neuronal recycling’, a process in which pre-existing brain structures, in this case object recognition systems in the ventral visual stream, are utilized for word recognition (Dehaene & Cohen, 2011). This view predicts that these repurposed systems are functionally specialized for reading-specific processes, albeit not necessarily fully so, since words and objects can still cause activity partially in the same brain systems (Dehaene & Cohen, 2011). Reading is perhaps the most complex skill that humans have to master without a specific genetic predisposition (Grainger, Rey, & Dufau, 2008). It is therefore not surprising that dyslexia is one of the most common learning disabilities, with a prevalence rate of 5 to 17.5 percent among school children (Saviour, Padakannaya, Nishanimutt, & Ramachandra, 2009; Shaywitz & Shaywitz, 2005). Dyslexia is characterized by an unexpected difficulty in learning to read and spell in children and adults who otherwise possess the intelligence, motivation, education, sociocultural opportunities and sensory abilities considered necessary for accurate and fluent reading (Saviour et al., 2009; Shaywitz & Shaywitz, 2005). Dyslexia is both familial and heritable, and family history is therefore an important risk factor (Shaywitz & Shaywitz, 2005).

People with dyslexia generally have a problem with fluent word recognition and are unable to read as many words in a given time as average readers (Shaywitz & Shaywitz, 2005). In contrast to typical readers, whose reading speed is largely independent of word length (Ward, 2015), dyslexics’ reading speed increases linearly with each additional letter (Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). This suggests that the reading in dyslexia is serial (letter-by-letter) rather than parallel like the reading of typical readers (Ziegler et al., 2003). Moreover, dyslexics often show decoding difficulties, that is they have trouble breaking words into individual phonemes and linking each letter to its corresponding sound. As a result, they are often inaccurate in identifying unfamiliar words and frequently have trouble comprehending what they read (Shaywitz & Shaywitz, 2005). However, studies have found that dyslexia ranges in severity from mild to severe and does not always have the same manifestation, since different individuals can have various symptoms of dyslexia to varying degrees (Nolen-Hoeksema, 2014).

Dyslexia is a major educational problem and can lead to serious difficulties at school and work (Saviour et al., 2009). The school dropout rate of dyslexics can be as high as 35%, which is twice the average school dropout rate in many countries. Furthermore, it has been estimated that less than 2% of dyslexics enrolled in undergraduate programmes in the USA complete their degree (Al-Lamki, 2012). Research also suggests that dyslexia has a negative effect on working practices and career progression (Al-Lamki, 2012). In addition, dyslexia can cause various psychological and social problems for the individual. Because dyslexics often have to work much harder in school than their non-dyslexic classmates, they frequently have low self-esteem (Al-Lamki, 2012). They are often anxious about their school difficulties, and can develop anxiety disorders (Al-Lamki, 2012). Dyslexics have been found to have more internalised behavior problems, such as depressive behaviors, and externalised behavior problems, such as delinquent behavior, than typical readers (Dahle, Knivsberg, & Andreassen, 2011). Further, studies suggest that dyslexia is underdiagnosed, which leads affected students to fall even farther behind in reading ability compared to their classmates (Arzubi & Martin, 2005).

Since people with dyslexia comprise a diverse group, it has proved difficult to determine its causes. Dyslexia is generally considered to have linguistic roots, and there is strong consensus among researchers that dyslexics are impaired in phonological processing, the ability to identify and manipulate the sound structure of words in a language (Du & Kelly, 2013; Sigurdardottir et al., 2015). In order to read, we must recognize that graphemes, that is letters and letter strings, represent phonemes, that is the sounds of a spoken language. For example, in English the letter ‘‘c’’ sometimes maps onto the phoneme ⁄k⁄and at other times onto the phoneme ⁄s⁄. As a result of increasing exposure to written language, children are likely to learn these grapheme and phoneme mappings implicitly. For instance, with increasing experience they are likely to detect that most words beginning with the letter ‘‘c’’ followed directly by the letter ‘‘i’’ have the phoneme ⁄s⁄as their initial phoneme (Arciuli & Simpson, 2012b). Such grapheme-phoneme awareness seems to be to some extent missing in dyslexic children and adults (Shaywitz & Shaywitz, 2005), and as a result they have trouble deconstructing written words into spoken speech sounds, preventing accurate word identification (Du & Kelley, 2013). However, the importance of phonological awareness in reading performance has been found to be greater for languages with opaque orthographies, in which a given letter is often pronounced differently in different words, than in shallow orthographies, in which a given letter is almost always pronounced the same in different words (Sigurdardottir et al., 2015; Ziegler et al., 2010). In addition, in some studies people with dyslexia exhibit satisfactory performance on standard phonological tests even if they fail to achieve fluency in reading, suggesting that they have problems with recognizing words fluently despite adequate knowledge of grapheme-phoneme correspondences (Pavlidou, Kelly, & Williams, 2010). This raises the possibility that dyslexia involves a more general learning deficit (Pavlidou et al., 2010).

Further problems experienced by dyslexics indicate difficulties in perceptual processes, motor coordination, attention, and memory (Everatt, Bradshaw, & Hibbard, 1999). Specifically, there is evidence for atypical visual processing in dyslexics and research has therefore focused on investigating abnormal processing of visual input as one source of dyslexia (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000). Studies show that dyslexics are generally slower and less accurate in processing non-linguistic visual information, such as lines, symbols, squares, and dots (Mayseless & Breznitz, 2011). Dyslexics also have difficulties in visual search and are less sensitive than typical readers to visual characteristics such as contrast and stimulus persistence (Vicari et al., 2005). Mayseless and Breznitz (2011) found that dyslexics process both real objects and pseudo-objects in a different way from typical readers, as longer reaction times and different brain activity patterns show. Furthermore, Sigurdardottir et al. (2015) found that dyslexics show impairments on recognition tasks that depend on discrimination between same-category objects, notably facial recognition. Based on their results, Sigurdardottir et al. (2015) concluded that dyslexics are specifically impaired at part-based processing of words, faces, and other objects, and that dyslexics' difficulty with reading might be the most obvious manifestation of a more general high level visual deficit (Sigurdardottir et al., 2015).

Studies of brain structure show differences between dyslexics and typical readers of all ages. Dyslexics have less gray matter in the left parietotemporal area, which probably leads to their impairment in phonological processing (Hudson, High, & Al Otaiba, 2007). In addition, many dyslexics have less white matter in this area than typical readers, and studies show that more white matter in this region is correlated with increased reading skill. Functionally, dyslexics show hypoactivation in areas involved in reading (Hudson et al., 2007). For example, Shaywitz et al. (1998; 2002) found that dyslexics show dysfunctional brain activity in both visual and language regions in the posterior cortex during reading. In addition, Brunswick, McCrory, Price, Frith, and Frith (1999) found that dyslexics consistently show reduced activation in the left inferior temporal gyrus, an area that is active in typical readers during reading, and also during visual phonological discrimination tasks and letter naming (Brunswick et al., 1999). Studies have also found reduced activity in the VWFA among dyslexics, which could explain the difficulty they show in word recognition (Fan, Anderson, Davis, & Cutting, 2014; Norton, Beach, & Gabrieli, 2014). Further, since the VWFA is sensitive to familiar letter sequences, dyslexics' abnormality in this area could also explain their typical reading strategy of reading words in a letter-by-letter fashion (Binder et al., 2006; Ziegler et al., 2003).

Implicit learning

Neural systems that differ in dyslexics and typical readers overlap with neural systems involved in some types of implicit learning (Bennett, Romano, Howard, & Howard, 2008). Implicit learning is defined as the process through which people become sensitive to certain regularities in the environment. This process occurs even without an intention to learn about those regularities and in the absence of awareness that one is learning. The resulting knowledge is thus difficult to express (Du & Kelly, 2013). Dyslexics show reduced activation in inferior frontal and left temporal-parietal areas compared to typical readers during language-based tasks. Imaging studies have also found that individuals with dyslexia have abnormal structure and function in the cerebellum and striatum (Bennett et al., 2008). All these areas have been found to be involved in various kinds of implicit learning (Bennett et al., 2008). Consistent with this overlap between brain regions involved in dyslexia and implicit learning, studies show that while explicit skill learning that requires effort is spared in dyslexia, some forms of implicit learning seem to be reduced (e.g. procedural learning and sequence learning; Bennett, et al., 2008; Lum, Ullman, & Conti-Ramsden, 2013). The role of implicit learning in dyslexia is not surprising, since learning to read involves implicit as well as explicit processes. Many researchers believe that children must implicitly develop knowledge of characteristics in their native language, such as syllables and rhymes, before they can explicitly learn phonological-orthographical correspondences and become explicitly familiar with phonological segments. They then continue to learn how phonology is mapped into its written representation implicitly (Du & Kelly, 2013; Folia, et al., 2008).

Studies suggest that the implicit procedural learning system, which underlies the learning, knowledge, and execution of motor and cognitive skills and habits, is impaired in dyslexia (Lum et al., 2013). Procedural learning processes are revealed when repeated exposure to a task results in improved performance on that task, regardless of whether this exposure is consciously remembered or not (Gómez-Beldarrain, García-Moncó, Rubio, & Pascual-Leone, 1998). The procedural learning system underlies a range of linguistic skills, for example the learning and use of syntax and grammar rules, morphology and phonology (Lum et al., 2013). Research suggests that dyslexia may be in part explained by impairments in parts of the procedural learning system that support language, especially phonology (Lum et al., 2013). These impairments presumably involve trouble with acquiring and adapting phonological knowledge, and automatizing skills necessary to support reading. Studies have reported procedural learning impairments in dyslexia on various tasks (e.g. Vicari et al., 2005). Further, neural abnormalities have been reported in dyslexics in various brain structures underlying procedural learning, including the cerebellum, the basal ganglia, and motor areas (Lum et al., 2013). Specifically, the cerebellum, which has been found to be important for procedural learning (Gómez-Beldarrain et al., 1998), has been indicated as the best biomarker of dyslexia (Pernet, Poline, Demonet, & Rousselet, 2009). Indeed, dyslexics show deficits in skill automatization, time estimation, and balance, indicating abnormal cerebellar function (Nicolson, Fawcett, & Dean, 2001).

There is also evidence that individuals with dyslexia learn less than typical readers while engaging in tasks that rely on implicit sequence learning (e.g. Bennett et al., 2008; Howard, Howard, Japikse, & Eden, 2006). Implicit sequence learning involves the acquisition of sequential regularities such as the perceptual sequence of visual and auditory stimuli (Bennett et al., 2008). Implicit sequence learning is most often studied using a serial reaction time task (SRTT), in which people respond to each of a series of visual stimuli by pressing a corresponding key. Sequence learning is revealed when people respond faster and more accurately to stimuli that follow a repeating sequence versus stimuli that occur at randomly determined locations (Bennett et al., 2008; Howard et al., 2006). Stoodley, Harrison, and Stein (2006) found that during a serial reaction time task, dyslexics' reaction times were comparable to those of typical readers during randomly ordered trials. However, dyslexics showed less decrease in reaction times compared to typical readers during a repeated sequence. Likewise, Vicari et al. (2005) found that dyslexic children were impaired on serial reaction time tasks, since they displayed similar responses to randomized and repeated sequences. In addition, implicit sequence learning depends on fronto-striatal-cerebellar circuitry, and research suggests that dyslexia might be associated with deficits in this circuitry (Howard et al., 2006).

It is therefore possible that dyslexics' difficulty in processing written words as efficiently as typical readers is one aspect of a general impairment in implicit learning (Vicari et al., 2005). However, the literature on implicit learning and dyslexia has yielded mixed results, and not everyone agrees that dyslexia involves a problem with implicit learning (Howard et al., 2006). For instance, the finding that procedural learning is impaired in dyslexia has not always been replicated (e.g. Menghini et al., 2010). In addition, Kelly, Griffiths, and Frith (2002) examined the performance of dyslexic participants in a serial reaction time task, and concluded that implicit learning is intact in dyslexia. Similarly, Deroost et al. (2009) found no difference in sequence learning between dyslexics and controls. This leaves open the question whether dyslexia does involve a deficit in implicit learning (Lum et al., 2013).

Interestingly, studies also indicate that dyslexics are not impaired in all kinds of implicit learning (Bennet et al., 2008). For instance, studies show that dyslexia does not involve a deficit in spatial context learning, which involves the learning of spatial regularities (Bennet et al., 2008; Howard et al., 2006). When assessing this kind of learning, participants may complete a task in which the global configuration of a display cues the location of a search target (Howard et al., 2006). Howard et al. (2006) found that while dyslexic individuals were impaired in implicit sequence learning, they showed unimpaired implicit learning of spatial context. Interestingly, their results demonstrated a positive correlation between reading ability and sequence learning, but a negative correlation between reading ability and spatial context learning (Howard et al., 2006). The presence of implicit learning impairments in dyslexia is therefore still a matter of debate. It is possible that instead of showing a profound deficit in implicit learning, dyslexics make much weaker associations and therefore need considerably more training for such learning to reach levels that are quickly displayed by typical readers (Du & Kelly, 2013). Furthermore, if dyslexia involves a general impairment in implicit learning, it is still not entirely clear if impaired implicit learning hinders the development of skills necessary for fluent reading, or if dyslexia causes impaired implicit learning of linguistic regularities (Du & Kelly, 2013).

Statistical learning

Another type of implicit learning is statistical learning (Arciuli & Simpson, 2012a), the ability to detect statistical regularities in the environment and use this information to make predictions and guide behavior (Bertels, Franco, & Destrebecqz, 2012). Statistical learning involves acquiring knowledge about transitional probabilities, which measure the frequency of one event (e.g. a word) given the presence of another event (Perruchet & Pacton, 2006).

Statistical learning seems to start operating almost as soon as people are exposed to stimuli that contain probabilistic associations (Arciuli & Simpson, 2011) and in the absence of any form of instruction to do so (Arciuli & Simpson, 2012a). It is also long lasting and consistent over time, remaining stable for hours after exposure to the stimuli (Arciuli & Simpson, 2012a). Studies suggest that statistical learning is developmentally invariant, with children possessing similar neural mechanisms as adults for learning statistical patterns (Jost, Conway, Purdy, Walk, & Hendricks, 2015).

Statistical learning is a general type of learning that can be found in many different domains (Mirman, Estes, & Magnuson, 2010). It is thought to be crucial for a wide range of perceptual and cognitive processes, such as object recognition and localization (Arciuli & Simpson, 2011). Objects appearing in a statistically consistent context are detected more accurately and processed more quickly than objects appearing in an inconsistent context (Oliva & Torralba, 2007). For example, when observers are presented with a scene of a familiar context, such as a kitchen, objects that are consistent with that context (e.g. a loaf of bread) are recognized more easily than objects that would not be expected in that context (e.g. a drum; Bar, 2004). Statistical learning also plays a key role in the predictions of everyday phenomena (Arciuli & Simpson, 2011), since learning statistical contingencies between objects causes the perception of one object to generate strong expectations about the plausible presence and location of other objects (Oliva & Torralba, 2007). Studies have found that people can learn statistical contingencies between novel objects, predicting the presence of one object based on the presence of another, over the course of only 30 minutes (Oliva & Torralba, 2007).

Furthermore, statistical learning seems to be important for language acquisition (Arciuli & Simpson, 2011). Words in a given language are characterized by patterns of transitional probabilities that constrain their possible phonological structure and the co-occurrences of letter strings (Pavlidou & Williams, 2014). This is also true regarding word patterns in sentences, since implicit knowledge of the probabilities in a language can enable a listener to better identify and predict the next word that will be spoken (Conway, Bauernschmidt, Huang, & Pisoni, 2009). When surrounding noise degrades parts of a spoken utterance, the listener must rely on implicit knowledge of regularities in the language to predict the next word that will be spoken based on previous spoken words. For example, when a sentence with a highly predictable ending, such as “her entry should win her first prize", and another sentence with a non-predictable ending, such as "the arm is riding on the beach", are presented to participants under degraded listening conditions, implicit knowledge of language structure can improve perception of the final word in the first sentence but not in the second sentence (Conway et al., 2010). Language can therefore be described in terms of statistical relations among language units (Conway et al., 2010). Research suggests that statistical learning might involve the coupling between language and vision, since the interaction between language and vision reflects experiential knowledge about a correspondence between transitional probabilities regarding elements in the language and transitional probabilities regarding elements in the real world (Altmann, 2002; Fiser & Aslin, 2002).

It is now widely believed that many behaviors that appear rule-governed, such as reading, are in fact driven by implicitly learned statistical regularities (Apfelbaum, Hazeltine, & McMurray, 2013). Reading involves automatically learning the orthographic and morphological regularities of written words (Misyak, & Christiansen, 2012), more specifically the correspondences between arbitrary visual symbols (i.e. letters) and the linguistically meaningful sounds of a language (Arciuli & Simpson, 2012b). There is a substantial body of evidence, both direct and indirect, supporting the view that implicitly learned regularities underlie reading (Apfelbaum et al., 2013; Arciuli & Simpson, 2012b). For instance, reading and word recognition are sensitive to statistical regularities between letters and sounds (Treisman & Kessler, 2006). Further, in learning to read, children do not seem to rely on abstract, general rules, but instead become sensitive to the frequency with which letters co-occur (Arciuli & Simpson, 2012b; Deacon, Conrad, & Pacton, 2008). In addition, Frost, Siegelman, Narkiss, and Afek (2013) found that when learning a second language with different statistical properties from their first language, people with a higher capacity for statistical learning were better at learning to read in the second language.

Arciuli and Simpson (2012b) examined the relationship between statistical learning and reading ability in typically developing children and healthy adults. To measure statistical learning their observers watched a continuous stream of evenly paced, individually presented items on a monitor. The items in this familiarization stream were grouped arbitrarily in triplets. The participants then had to perform a forced-choice task indicating which stimuli had come together in triplets during the familiarization phase. Reading ability was examined by administering the reading subtest of the Wide Range Achievement Test (Arciuli &

Simpson, 2012b). Statistical learning capacity was a significant predictor of reading ability in both children and adults after controlling for age and attention. Participants who learned more of the transitional probabilities embedded in the familiarization stream of the statistical learning task demonstrated higher reading ability. The study provides evidence that a capacity for more effective statistical learning is related to higher reading ability in the general population (Arciuli & Simpson, 2012b).

Studies examining statistical learning in the brain have found that some brain areas involved in statistical learning are also involved in dyslexia. For instance, statistical learning recruits known memory systems, including the medial temporal lobe and striatum (Shapiro & Turk-Brown, 2015). The role of the striatum in statistical learning is important, since neural abnormalities in the striatum have been reported in dyslexics (Bennet et al., 2008). Furthermore, the inferior frontal gyrus has been found to be involved in segmenting regularities in both the auditory and visual domains (Shapiro & Turk-Brown, 2015). This is interesting considering the fact that dyslexics show structural anomalies in the inferior frontal lobe including the inferior frontal gyrus (Clark & Plante, 1998). Moreover, Turk-Brown, Scholl, Chun, and Johnson (2009) found that the left fusiform gyrus responds to statistical structure, as shown by enhanced responses to structured relative to random blocks. These results are particularly relevant since the VWFA, which has been found to be abnormal in dyslexics (Fan et al., 2014), is located in the left fusiform gyrus (Woodhead et al., 2011). However, to our knowledge, no study has thus far examined the role of statistical learning in dyslexia. Because of the relationship between statistical learning ability and reading ability, and the fact that neural systems that differ in dyslexics and typical readers overlap with neural systems involved in statistical learning, it is quite plausible that dyslexics have a lower capacity for statistical learning compared to typical readers.

Related factors

In assessing the link between dyslexia and implicit learning abilities, it is important to control for other factors that are related to general learning abilities such as attention deficit hyperactivity disorder (ADHD) and intelligence. ADHD is one of the most prevalent developmental disorders, characterized by excessive activity, short attention span, and impulsivity (Germanó, Gagliano, & Curatolo, 2010). There is substantial evidence for the comorbidity of dyslexia and ADHD (Germanó et al., 2010). There seems to be a bidirectional relationship between the two disorders, since the comorbidity is high both when children with dyslexia are tested for ADHD and when children with ADHD are tested for dyslexia. In samples of children with dyslexia up to 42% also meet criteria for ADHD (Germanó et al., 2010). Interestingly, research suggests that, similarly to dyslexia, some kinds of implicit learning are atypical in individuals with ADHD (Barnes, Howard, Howard, Kenealy, & Vaidya, 2010). Moreover, studies have shown that individuals with reading difficulties plus ADHD have more severe learning problems than individuals with only one of the conditions (Germanó et al., 2010).

To be diagnosed as dyslexic, a person has to be of adequate intelligence (Gustafson & Samuelsson, 1999), that is he or she cannot have an intellectual disability that could explain their reading difficulties. However, research has produced mixed results concerning the link between dyslexia and intelligence. Some studies have indicated a small or nonexistent link between the two (e.g. Gustafson & Samuelsson, 1999), while others have found significantly lower intelligence, both verbal and nonverbal, in dyslexics compared to typical readers (e.g van Bergen et al., 2014). The role of intelligence in dyslexia therefore remains undecided. Individual differences in implicit learning are generally expected to be largely independent of individual differences in intelligence, since it is assumed that implicit learning is evolutionarily older than the cognitive mechanisms underlying intelligence (Kaufman, DeYoung, Gray, Jiménez, Brown, & Mackintosh, 2010). However, some studies have found that implicit learning is related to intellectual ability, in that higher intelligence predicts superior implicit learning abilities (e.g. Fletcher, Mayberry, & Bennett, 2000).

Further, when determining the link between dyslexia and implicit learning abilities, it is advisable to control for handedness. Handedness is associated with brain hemispheric asymmetries, and there is a weak correlation between language lateralization and handedness, where 96% of strong right-handers show left-hemisphere dominance for language, as compared with 73% of strong left-handers (Brandler & Paracchini, 2014). The association between brain lateralization and handedness is important because neuroimaging studies suggest that atypical or weak cerebral lateralization is related to dyslexia (Brandler & Paracchini, 2014). Indeed, there is an elevated frequency of dyslexia in left-handed individuals and in their families (Geschwind & Behan, 1982). In addition, statistical learning is dependent on certain lateralized brain areas such as the left fusiform gyrus (Turk-Brown et al., 2009). Therefore, it is possible that handedness could affect the association between dyslexia and statistical learning.

The current study

The purpose of the current study is to determine whether poor capacity for statistical learning is related to dyslexia. To do this, we directly compare the performance of individuals with dyslexia and individuals with no reading difficulties on a well-established statistical learning test modeled on previously published tasks (e.g. Arciuli & Simpson, 2012b; Turk-Browne, Scholl, Chun, & Johnson, 2009). Since it is unclear whether individual differences in ADHD, intelligence, and handedness affect individual differences in statistical learning, we control for these three variables when comparing dyslexics' and typical readers' performance on the statistical learning task. Since there is evidence for abnormal visual processing in dyslexia, we will also control for participants' visual recognition abilities.

Methods

Participants

Two groups of 40 people each participated in the study. Out of the 80 participants, seven were immediately resampled because one participant did not meet requirements for normal or corrected to normal vision, two participants fell asleep during the statistical learning test, and four participants' responses on the statistical learning test were not recorded, for unknown reasons. One group consisted of adults with a prior diagnosis of dyslexia (23 women). The other group consisted of adult typical readers (23 women). The mean age in the dyslexic group was 27.2 years (range 19 to 60 years). The mean age in the typical readers group was 26.6 years (range 18 to 56 years). Participants were only included if they did not test positive when screened for color blindness, and if they had normal hearing and normal or corrected to normal vision.

Participants in the two groups were matched, so that for each dyslexic subject, there was a typical reader of the same gender, same age (+/- 5 years), and with a similar educational background (completed primary school, high school, undergraduate or graduate university degrees). In each group 15 participants had completed primary school or less, 20 had completed high school, 5 had completed an undergraduate university degree and no one had completed a graduate university degree. All participants were volunteers. They were not paid for participation, but everybody participated in a lottery where five randomly selected participants received a gift card for approximately $75 to be used in a local shopping center.

In addition, participants who were at the time enrolled in a specific course at the University of Iceland could receive partial course credit for their participation.

Test materials

Nonverbal intelligence. Block Design and Matrix Reasoning subtests from the Icelandic version of the Wechsler Adult Intelligence Scale (WAIS-III; Kaufman & Lichtenberger, 1999; Líndal, Jónsdóttir, Másson, Andrason & Skúlason, 2005) were used as a measure of nonverbal intelligence. The reliability of WAIS-III is well established (Kaufman & Lichtenberger, 1999). Block Design and Matrix Reasoning are two out of seven nonverbal scales in the WAIS-III. The nonverbal scales are designed to measure spatial, sequencing, and problem-solving skills and do not rely on reading skills (Kaufman & Lichtenberger, 1999).

The Block Design subtest measures spatial problem-solving, manipulative abilities and part-to-whole organization. It consists of nine red and white square blocks and a stimulus booklet with model forms. The examinee must arrange the blocks to match a model form shown in the booklet. Each item is scored both for accuracy and for speed. An accurate solution gives a score from zero to seven depending on how fast the examinee arranges the blocks. An inaccurate solution gives a score of zero. When an examinee gets three consecutive scores of zero, the administration of the Block Design subtest is discontinued. Each examinee gets a total score from zero to 68 (Kaufman & Lichtenberger, 1999).

The Matrix Reasoning subtest measures nonverbal analytical reasoning. The examinee is presented with a series of pictures with a part missing. The examinee chooses the missing part that will complete the picture, from five choices. For each correct answer the examinee gets a score of one, and each incorrect answer gives a score of zero. When an examinee gets four consecutive scores of zero, or four scores of zero on any five consecutive items, the administration of the Matrix Reasoning subtest is discontinued. Each examinee gets a total score from zero to 26. Since the WAIS-III has not been standardized for the Icelandic population, we computed standardized scores for each subtest using British norms. Since these scores are not being used for clinical purposes, we assume this is sufficient for our study.

Reading abilities. Two tests were administered to verify the difference in reading abilities between the two groups. The Icelandic version of the Adult Reading History Questionnaire (ARHQ-Ice; Bjornsdottir et al., 2013) was used to detect participants' history of reading difficulties indicative of dyslexia. The questionnaire consists of 22 questions for which possible answers range from zero to four. The total score for each subject is divided by the maximum total score (88) where each subject gets a score from zero to one. A score above 0.43 is considered to predict dyslexia. The Icelandic adaptation of the ARHQ has been proven a reliable and valid screening instrument for dyslexia (Bjornsdottir et al., 2013).

The IS-FORM reading test (Sigurdardottir et al., 2015) was used to assess participants' current reading ability. Originally the test consisted of two lists of words, one with 128 common Icelandic word forms and another with 128 uncommon word forms. In the current study a third list with 128 pseudo-words was added, since studies suggest that one of the most sensitive measures of dyslexia is an inability to read phonologically valid pseudo-words (Shaywitz et al., 1998). Since the word forms in the IS-FORM reading test are of such varying difficulty, the test captures a wide variety of reading ability (Sigurdardottir, et al., 2015). Of interest in the current study are words read per minute and percentage of correctly read word forms.

Behavioral assessment. Two questionnaires of ADHD symptoms as defined by the DSM-IV were used to to assess ADHD (Magnússon et al., 2006). The first questionnaire is a self-report of current symptoms where the frame of reference is the participant's behavior in the past six months. The second questionnaire is a self-report of childhood symptoms where the frame of reference is the participant's behavior in the age period 5 to 12 years. Each questionnaire consists of 18 questions with possible answers on a 4-point scale (never or rarely, sometimes, often, very often). Total scores for both questionnaires are calculated so that each participant gets a score from zero to 54. A score of 25.8 or above for childhood symptoms and a score of 32.5 or above for current symptoms are required to screen positive for ADHD. These questionnaires have been proven to be a reliable and a valid screening instrument for ADHD (Magnússon et al., 2006).

Handedness. The Icelandic shortened version of Edinburgh Handedness Inventory (Oldfield, 1971) was used to acquire information about hand preference and orientation. The inventory consists of 10 questions where respondents are asked to indicate their hand preferences when performing specific activities, for example writing and brushing teeth. The questionnaire also consists of two questions that assess participants' dominance of right and left leg, and right and left eye. Participants indicate their preference by putting one plus sign (+) in the appropriate column ("left" or "right") for each activity. If the preference is so strong that participants would never try to use the other hand, foot or eye unless absolutely forced to, they are told to put two plus signs in the appropriate column. If participants have no preference at all they are told to put a plus sign in both columns. The number of plus signs in each column is used to calculate a laterality quotient for each participant. The laterality quotient ranges from -100 to +100 and a positive score indicates right-handedness while a negative score indicates left-handedness. The reliability for Edinburgh Handedness Inventory is not ideal but it is sufficient for our purposes.

Statistical learning. As a measure of statistical learning a visual processing test was developed. The test was modeled on previous research on the statistical learning of temporal transitional probabilities (notably, Arciuli & Simpson, 2012b; Turk-Browne et al., 2009). The statistical learning test consisted of a familiarization phase with a cover task, a shape recognition control test, and a two-alternative forced-choice familiarity test.

The stimuli consisted of 48 shapes similar to those used in previous studies on statistical learning (e.g. Fiser & Aslin, 2001; Turk-Browne et al., 2009). The shapes were from unfamiliar writing systems and had likely never been encountered before by participants (e.g. from the Sabean and Santali alphabets). Multiple alphabets were used to increase shape discriminability. For each matched pair of participants, 12 of the 48 available shapes were randomly assigned without replacement to the familiarization phase and another 12 to the shape recognition control test. In the familiarization phase the 12 shapes were furthermore divided into six base pairs.

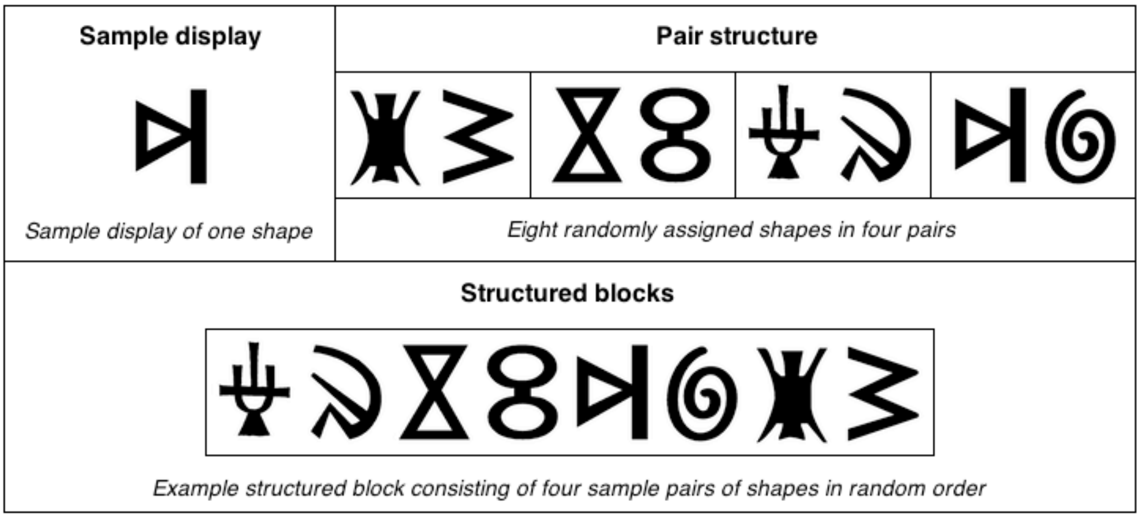

Figure 1. Stimuli in the statistical learning task

The familiarization phase consisted of displaying the six base pairs in a continuous stream of sequential stimuli (*Figure 1*), with one shape shown at a time. The two shapes that made up each pair always appeared together in the same order during the familiarization phase. There were no pauses between the appearance of the shapes, and the underlying structure of the pairs was unknown to the participants. During the familiarization phase each shape was shown in isolation in the center of the display and appeared in black on a white background. 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. These jiggle-trials occurred randomly in one out of every six shape presentations. The cover task made sure that participants were paying attention to the familiarization stream by requiring them to press a button every time a shape jiggled.

In the shape recognition control test the 12 base shapes displayed in the familiarization phase were pitted against 12 unfamiliar foil shapes that were not presented in the familiarization phase and 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. After the presentation of the second shape participants identified which of the two shapes had previously appeared in the familiarization phase. Each base shape was pitted against four random foils. 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. Each base shape and each foil shape were displayed four times each for a total of 48 randomized trials. The reason why the statistical learning task involves a shape recognition control test is that for statistical learning to take place, it is necessary that single shapes be recognized. Any difference between participants in the perception of single shapes will inevitably be reflected in statistical learning performance, since a shape that is not perceived might not be paired into a larger perceptual unit. For this reason, we decided to only include data from participants responding over 50% correct in the shape recognition control test, since that indicates recognition of the shapes.

For the two-alternative forced-choice familiarity test six additional 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 a second shape in another. For each test trial one base pair was displayed along with one foil pair, presented one at a time. After the last shape in the trial had been displayed, participants identified which of the two pairs had appeared previously in the familiarization phase. A preference for base pairs over foils was taken as an indication of statistical learning. During the two-alternative forced-choice familiarity test each base pair was pitted against each foil pair on two separate occasions. Across 72 randomized test trials each base pair and each foil pair were presented an equal number of times, or 12 times each.

The shapes assigned to each part of the statistical learning test (i.e. the familiarization phase, the shape recognition control test and the two-alternative forced-choice familiarity test) and the order of their presentation was the same for each matched participant pair. This ensured that viewing specific stimuli did not influence the degree to which the matched pair differed on their performance. The stimuli were presented using PsychoPy, an open-source application written in Python.

Procedure

The study was approved by the Icelandic Science Review Board and the Data Protection Authority. It took place in a quiet room with only one participant in each experimental session. Before participating in the study participants gave informed consent (if they preferred, the consent form was read aloud by experimenters). Each participant first answered questions regarding diagnoses he or she had received in the past (e.g. diagnoses of dyslexia, ADHD and autism). Then the two subtests of the WAIS-III intelligence test were administered. The Block Design subtest was administered first. Participants were shown the blocks and their different colored sides, and asked to arrange them in a specific way. Then they watched one of the experimenters arrange the blocks to look like a particular model form in the booklet, and were asked to do the same. This was repeated for a maximum of thirteen other model forms (depending on performance), except without the experimenter modeling the block arrangement. The participants were asked to work as fast as they could and tell the experimenter when they had finished their solution.

The Matrix Reasoning subtest was administered next. The participants were first shown three incomplete pictures and five possible choices that would complete the picture. They were told to carefully look at the picture and the choices, and try to choose the alternative that would best fit the picture's pattern. These three tasks were simple and were administered to ensure that the participants would understand how they were supposed to solve the tasks. Next the participants were shown a maximum of 23 more incomplete pictures (depending on performance) with increasing difficulty and asked to indicate which of the five choices would complete the picture.

After completing the two subtests of WAIS-III the participants answered the Edinburgh Handedness Inventory, the two questionnaires on ADHD symptoms and the Adult Reading History Questionnaire. If the participants preferred, the questionnaires were read aloud by experimenters. If they preferred to read the questionnaires themselves, the experimenters stepped outside and gave the participants privacy to answer the questions.

After answering the questionnaires the participants were asked to sit in front of a computer screen (distance approx. 60 cm) and complete the statistical learning test. First, participants completed the familiarization phase test, which lasted for approximately 20 minutes with four breaks. Participants were asked to watch the shapes that appeared on the computer screen and note their appearance. In addition, they were told to push the space button each time a shape jiggled. Next the participants completed the shape recognition control test which lasted approximately five minutes. In each session in this test, participants were asked to specify which shape of two alternatives had appeared in the familiarization phase, by pushing one of two keys on the keyboard. Finally, participants completed the two-alternative forced-choice familiarity test which lasted approximately 10 minutes with one break. In this test participants had to specify which shape pair of two alternative pairs had always appeared together in the familiarization phase, by pushing one of two keys on the keyboard.

The IS-FORM was administered last for each participant. The word lists were put in front of the participant one at a time and he or she was told to read the words on the list into a microphone as fast as they could while making as few errors as possible. Before reading the words on the third word list, participants were informed that the list consisted of pseudo-words.

Statistical analysis

The difference between dyslexics and typical readers was assessed on the aforementioned measures using Statistical Package for the Social Sciences (SPSS, 22). An alpha level of 0.05 was used for statistical tests which were all two-sided. Independent-Samples T-tests were used to determine the difference between dyslexics and typical readers on nonverbal intelligence, ADHD, handedness and scores on the shape recognition control test. Linear Regression Analyses were used to assess the difference between the two groups in the percentage correct in the two-alternative forced-choice familiarity test. To be able to use regression analysis, we dummy-coded our independent variable so that the number 1 indicated that a participant was dyslexic and the number 0 indicated that a participant was a typical reader. Effect sizes were estimated using Pearson's r, Cohen's d, r-squared and f-squared. One participant pair was excluded from the sample in all analyses because the typical reader in this pair was a clear outlier on the two-alternative forced-choice familiarity test with only 11% accurate responding, which deviates markedly from chance performance. In addition, his responses indicated that he misunderstood what he was supposed to do on this test, and responded contrary to instructions.

Results

Typical readers scored higher, on average, on the Block Design and Matrix Reasoning subtests in the WAIS-III compared to dyslexics (*Table 1*). However, the difference between the two groups is not significant on either subtest, $t(76) = -0.11$, $p = 0.913$, $d = -0.03$ for Block Design, and $t(76) = -1.81$, $p = 0.074$, $d = -0.41$ for Matrix Reasoning. The scores of both dyslexics and typical readers on each subtest have similar variability, which further supports the conclusion that dyslexics' and typical readers' performance on nonverbal intelligence tests does not differ. The highest possible score on the Block Design subtest is 19, which is the highest score in both groups. Likewise, the highest possible score on the Matrix Reasoning subtest is 18, which is the highest score in both groups. The lowest possible score on both subtests is zero, however the lowest score on both subtests is noticeably higher in each group.

Dyslexics had higher scores, on average, on the ADHD screening test for both childhood symptoms and current symptoms (*Table 1*). This difference is significant for both childhood symptoms, $t(76) = 5.29$, $p < 0.001$, $d = 1.20$, and current symptoms, $t(76) = 3.53$, $p = 0.001$, $d = 0.80$. When raw scores are converted into a dichotomous ADHD screening score for each participant according to the test's manual, the group difference is no longer significant, $t(76) = 1.00$, $p = 0.320$, $d = 0.27$. In addition, scores on both childhood and current ADHD symptoms are more variable in the dyslexic group than in the typical readers group. The highest possible score on both current and childhood symptoms questionnaires is 54, and as can be seen in *Table 1*, dyslexics' highest score on both questionnaires is much closer to 54 than is the highest score of typical readers.

Table 1. Descriptive statistics for dyslexics and typical readers

	Dyslexics				Typical Readers			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Nonverbal Intelligence								
Block Design	12.77	3.14	7	19	12.85	3.06	6	19
Matrix Reasoning	11.79	2.94	5	18	12.97	2.81	6	18
Behavioral Assessment								
Childhood ADHD symptoms	25.03	13.21	5	51	11.59	8.80	2	38
Current ADHD symptoms	16.64	10.43	3	49	10.05	5.22	3	22
Reading Abilities								
ARHQ	0.62	0.12	0.42	0.88	0.28	0.08	0.08	0.45
Common Words Read /Minute	76.74	14.52	44	108	109.31	24.92	61	175
Common Words Accurate (%)	91.57	7.25	68.8	100	97.12	2.94	86.7	100
Uncommon Words Read/Minute	49.28	11.47	27	77	78.10	16.48	53	114
Uncommon Words Accurate (%)	77.00	13.28	40.6	97.7	92.57	5.04	78.9	98.4
Pseudo-words Read/Minute	35.26	9.67	14	60	55.05	11.94	30	85
Pseudo-words Accurate (%)	61.18	18.16	15.6	91.4	82.45	10.76	44.5	94.5
Shape Recognition								
Shape Recognition Ctrl Test (%)	95.94	6.14	64.58	100	98.18	3.58	79.17	100
Handedness								
Edinburgh Inventory	51.04	52.76	-83.3	100	69.02	31.51	-67.0	100

There was a clear difference between dyslexics and typical readers on measures of reading ability. The ARHQ screening test and the six measures in the IS-FORM reading test were used to verify the difference in reading abilities between the two groups. Dyslexics had, on average, considerably higher scores on the ARHQ screening test compared to typical readers (*Table 1*), higher scores meaning more indicators of dyslexia. Both dyslexics' and typical readers' scores have rather little variability, indicating that most participants had scores that don't fall far from the mean. Possible scores on ARHQ range from 0 to 1, but no participant in either group had a score of 0 nor a score of 1. Participants with a score above 0.43 screened positive for dyslexia.

The lowest score in the dyslexic group on ARHQ was much higher than that of typical readers, since almost all dyslexic participants had scores above 0.43. However, two participants with a dyslexia diagnosis scored slightly below the cutoff point and therefore screened negative for dyslexia on the ARHQ screening test, with scores of 0.42 and 0.43. However, since these scores are so close to the cutoff point, and these participants' performance on the IS-FORM reading test was closer to that of other dyslexics than that of typical readers, these participants were still considered to belong to the dyslexic group. In addition, the highest ARHQ score in the typical reader group was much lower than that of dyslexics, since almost all typical readers had scores below the cutoff point. Only one participant in the typical reader group had a score above the cutoff point and therefore screened positive for dyslexia, with a score of 0.45. However, since this score is also very close to the cutoff point, and this participant's performance on the IS-FORM reading test was closer to that of other typical readers than that of dyslexics, this participant was still considered to belong to the typical readers group. ARHQ scores were highly correlated with dyslexia diagnoses, when used as continuous scores: r = 0.85, and also when used as dichotomous screening scores: r = 0.95, both significant at the 0.01 level. This supports the assumption that participants diagnosed with dyslexia had considerably higher scores on the ARHQ screening test compared to typical readers. The fact that ARHQ scores had such a high correlation with dyslexia diagnosis also supports the distinction between the two groups.

Participants with a dyslexia diagnosis performed more poorly on the IS-FORM reading tests compared to typical readers (*Table 1*). Dyslexics read considerably fewer words per minute than typical readers, both common word forms, uncommon word forms and pseudo-word forms. In addition, dyslexics had a lower proportion of accurately read word forms on all word lists compared to typical readers. Typical readers had more variable performance in terms of words read per minute on all word lists, but dyslexics had more variable performance in terms of accurate read word forms on all word lists. All the IS-FORM measures were moderately to highly negatively correlated with dyslexia diagnosis, with correlations ranging from $r = -0.45$ to $r = -0.72$. All correlation coefficients were significant at the 0.01 level. This supports the assumption that dyslexics had poorer performance on the IS-FORM reading tests compared to typical readers. This also indicates that performance on this reading test supports the distinction between the two participant groups.

Typical readers scored higher, on average, on the shape recognition control test compared to dyslexics (*Table 1*). This difference does not, however, reach significance, $t(76) = -1.97$, $p = 0.052$, $d = -0.45$. There is noticeably more variability in accurate responding in the dyslexic group compared to the typical reader group, the standard deviation being nearly twice as large in the former compared to the latter group. Further support for this can be seen in the minimum percent correct, which is 64.58% in the dyslexic group but 79.17% in the typical readers group, while maximum percent correct is 100% in both groups. More importantly, all participants performed over 50% correct, showing that participants in both groups recognized the shapes.

Typical readers also had higher scores, on average, on the Edinburgh Handedness Inventory compared to dyslexics (*Table 1*), but the difference between the two groups was not significant, $t(76) = -1.83$, $p = 0.072$, $d = -0.41$. Further, dyslexics' scores on the questionnaire are more variable than typical readers' scores. The lowest possible score on the questionnaire is -100 (indicating strong left-handedness), and as can be seen on *Table 1*, dyslexics' lowest score is somewhat closer to -100 than the lowest score of typical readers. The highest possible score on the questionnaire is 100 (indicating strong right-handedness), which is the highest score in both groups.

The most important finding was that participants diagnosed with dyslexia showed, on average, less accurate responding on the two-alternative forced-choice familiarity test compared to typical readers, or 66.56% correct compared to 77.74%, respectively (*Figure 2*).

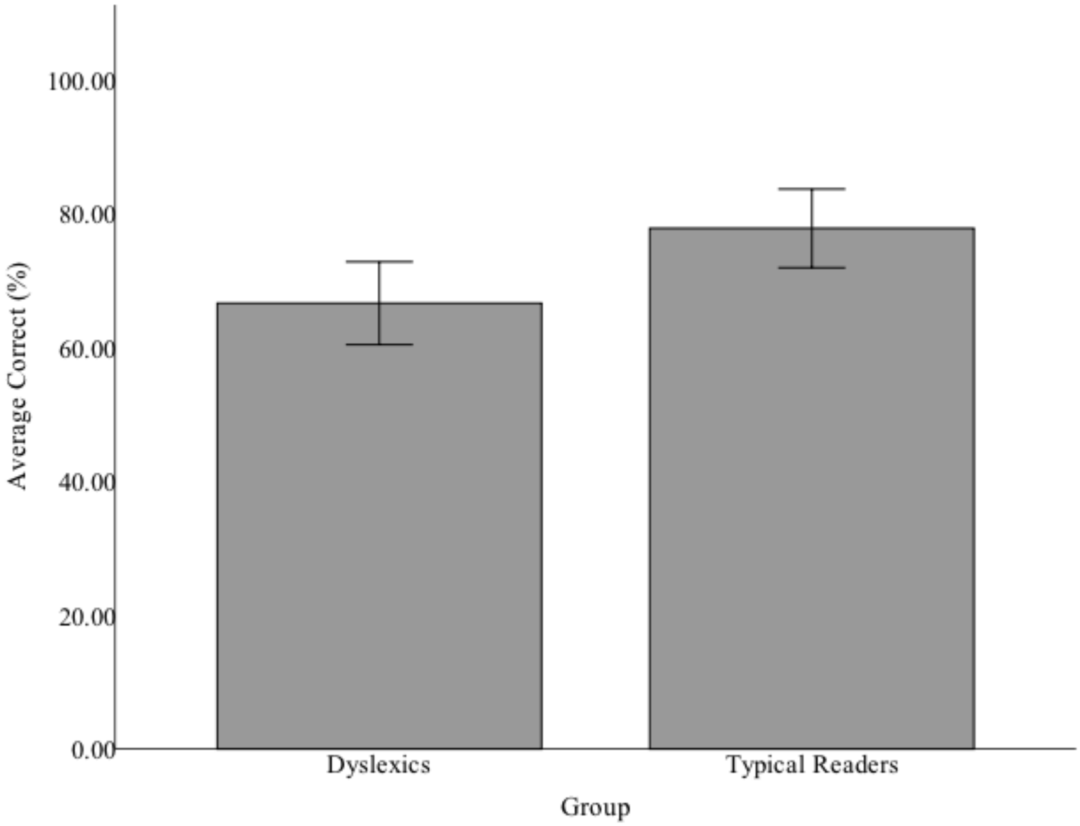

Figure 2. Average correct (%) for dyslexics and typical readers in the two-alt. forced-choice test

Dyslexics' capacity for statistical learning was therefore poorer than that of typical readers. Since the standard error bars overlap only slightly, it is unlikely that the difference in this study is coincidental. In addition, the error bars are quite small, which further supports the conclusion that the difference between the performance of dyslexics and typical readers in the two-alternative forced-choice familiarity test is true for the population.

An initial linear regression analysis on the association between dyslexia and statistical learning abilities where the effects of potential third variables was not controlled for explained 8.3% of the variance in the performance on the two-alternative forced-choice familiarity test, $f^2 = 0.09$. Dyslexia was a significant predictor of performance on the two-alternative forced-choice familiarity test, $\beta = -11.18$, $t = -2.62$, $p = 0.011$. This is equivalent to a decrease of approximately eleven percentage points in accurate responding on the forced-choice test for dyslexics compared to typical readers, which is in accordance with the mean difference between the two groups (see *Table 1*).

A linear regression analysis was run in which the effects of scores on Block Design and Matrix Reasoning was controlled for. As a whole, this model explained about 15% of the variance in performance on the two-alternative forced-choice familiarity test, $f^2 = 0.18$. Dyslexia was still a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for scores on nonverbal intelligence measures, $\beta = -11.03$, $t = -2.58$, $p = 0.012$. Dyslexia therefore still predicted a decrease of approximately eleven percentage points in performance on the forced-choice test when participants' nonverbal intelligence was held constant.

A linear regression analysis was run in which the effects of performance on nonverbal intelligence measures and results on the ADHD screening test were controlled for. As a whole, this model explained just over 16% of the variance in performance on the two-alternative forced-choice familiarity test, $f^2 = 0.20$. Dyslexia was still a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for scores on nonverbal intelligence measures and whether or not participants screened positive for ADHD, $\beta = -10.53$, $t = -2.45$, $p = 0.017$. Dyslexia therefore predicted a decrease of approximately ten and a half percentage points in performance on the forced-choice test when both participants' nonverbal intelligence and ADHD were held constant. However, it is worth considering that when the scores on the ADHD screening test were used as continuous scores without converting them into a dichotomous screening score, dyslexia was not a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for childhood ADHD symptoms plus nonverbal intelligence, $\beta = -5.14$, $t = -1.07$, $p = 0.288$. On the other hand, dyslexia was still a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for current ADHD symptoms plus nonverbal intelligence, $\beta = -9.84$, $t = -2{,}11$, $p = 0.038$. However, since this test is designed for giving dichotomous scores it is more appropriate to control for the dichotomous ADHD scores when assessing dyslexia's predictability of the performance on the two-alternative forced-choice familiarity test.

A linear regression analysis was run in which performance on nonverbal intelligence measures, results on the ADHD screening test and participants' performance on the shape recognition control test were controlled for. As a whole, this model explained almost 19% of the variance in performance on the two-alternative forced-choice familiarity test, $f^2 = 0.23$. Dyslexia was still a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for scores on nonverbal intelligence measures, whether or not participants screened positive for ADHD, and their performance on the shape recognition control test, $\beta = -9.12$, $t = -2.09$, $p = 0.041$. Dyslexia therefore predicted a decrease of approximately nine percentage points in performance on the forced-choice test when participants' nonverbal intelligence, ADHD and shape recognition abilities were held constant.

Finally, a linear regression analysis was run in which performance on nonverbal intelligence measures, results on the ADHD screening test, participants' performance on the shape recognition control test, and scores on Edinburgh Handedness Inventory were controlled for. As a whole, this model also explained almost 19% of the variance in performance on the two-alternative forced-choice familiarity test, $f^2 = 0.23$. Dyslexia was still a significant predictor of performance on the two-alternative forced-choice familiarity test after controlling for scores on nonverbal intelligence measures, whether or not participants screened positive for ADHD, shape recognition abilities, and handedness, $\beta = -9.16$, $t = -2.04$, $p = 0.045$. Dyslexia therefore still predicted a decrease of approximately nine percentage points in performance on the forced-choice test when participants' nonverbal intelligence, ADHD, shape recognition abilities, and handedness were held constant.

Discussion

Statistical learning is a general type of learning thought to be crucial for a wide range of perceptual and cognitive processes, such as object recognition and language (Arciuli & Simpson, 2011; Mirman et al., 2010). In addition, in recent years researchers have examined the role of statistical learning in reading. Since reading involves learning the orthographic and morphological regularities of written words (Misyak & Christiansen, 2012), researchers have speculated that statistical learning underlies reading. Recent studies provide evidence supporting this hypothesis (Apfelbaum et al., 2013; Arciuli & Simpson, 2012b). For instance, studies have found that statistical learning ability is positively related to reading ability in both children and adults in the general population (Arciuli & Simpson, 2012b), and that higher statistical learning ability is associated with superior reading acquisition in a second language (Frost et al., 2013).

Since statistical learning is thought to underlie reading, the purpose of the current study was to determine whether poor capacity for statistical learning is related to dyslexia.

Our results show that dyslexics are impaired in statistical learning, as shown by poorer performance on the two-alternative forced-choice familiarity test compared to typical readers. This indicates that the difficulty dyslexics show in reading might be related to a general impairment in statistical learning. These results are in accordance with previous studies showing that capacity for statistical learning is related to reading ability (Arciuli & Simpson, 2012b; Frost et al., 2013). In addition, these results are consistent with the finding that dyslexic individuals show abnormalities in brain areas involved in statistical learning, such as the striatum, the inferior frontal gyrus, and the left fusiform gyrus (Bennet et al., 2008; Clark & Plante, 1998; Fan et al., 2014; Shapiro & Turk-Brown, 2015; Turk-Brown et al., 2009).

Previous research suggests that individuals with dyslexia are impaired in object recognition. Dyslexics are slower and less accurate in processing and recognizing both linguistic and nonlinguistic visual information (e.g. Facoetti et al., 2000; Mayseless & Breznitz, 2011; Sigurdardottir et al., 2015). In contrast to previous research, our study did not find significantly poorer visual recognition in dyslexic participants compared to typical readers, as indicated by performance on the shape recognition control test. However, it is worth noting that the effect was marginal as the *p*-value was very close to being significant, suggesting that our results are not completely incompatible with previous research. Importantly, our results indicate that dyslexics' impairment in statistical learning involves more than impaired visual object recognition, since the difference in statistical learning between the two groups held after controlling for participants' performance on the shape recognition control test. This is consistent with the finding that statistical learning is a general type of learning (Mirman et al., 2010) and supports the idea that dyslexia involves a more general learning deficit than poor object recognition or phonological processing on their own (Pavlidou et al., 2010).

We did not find a difference between dyslexics and typical readers in nonverbal intelligence, supporting studies that have found a small or nonexistent link between dyslexia and intelligence (e.g. Gustafson & Samuelsson, 1999). More importantly, our results indicate that dyslexics' impairment in statistical learning is independent of nonverbal intelligence, since the difference in statistical learning ability between dyslexics and typical readers held after controlling for participants' performance on two measures of nonverbal intelligence. This is consistent with the assumption that individual differences in implicit learning are independent of individual differences in intelligence (Kaufman et al., 2010). These results indicate that individual differences in statistical learning capacity cannot be explained by differences in intelligence. They also suggest that everyone can be trained in the ability for statistical learning, independent of their cognitive abilities.

Our results also indicate that dyslexics' impairment in statistical learning is independent of ADHD since this impairment held after controlling for ADHD screening. However, only one participant screened positive for ADHD on this test, while 11 participants already had an ADHD diagnosis. Interestingly, the one participant who screened positive did not have an ADHD diagnosis and the 11 participants who already had an ADHD diagnosis did not screen positive for ADHD on this screening test. In this study the screening scores were considered to be more appropriate for use than ADHD diagnoses, since ADHD is most often diagnosed in childhood and symptoms often decline with age (Nolen-Hoeksema, 2014). It is possible that the participants who had an ADHD diagnosis but did not screen positive for ADHD had gotten their diagnosis in childhood but their symptoms had weared off with age. All the participants diagnosed with ADHD were in the dyslexic group, which is in accordance with studies showing high comorbidity between dyslexia and ADHD (Germanó et al., 2010). The only participant who screened positive for ADHD was in the typical readers group, which is inconsistent with participants' former ADHD diagnoses.

Dyslexics had more ADHD symptoms according to the ADHD screening test, and the difference in statistical learning ability between dyslexics and typical readers did not hold when controlling for ADHD symptoms. However, the symptom scores are continuous (i.e. raw scores not converted into a dichotomous screening score), and this test is designed as a screening tool with the purpose of distinguishing between ADHD positives and ADHD negatives, and not for providing continuous ADHD scores. Using the dichotomous screening scores is thus more appropriate than using the continuous raw symptom scores. Dyslexics' impairment in statistical learning therefore seems to be independent of ADHD, which indicates that ADHD does not influence the association between statistical learning and dyslexia.

Dyslexics and typical readers did not differ significantly in their scores on the Edinburgh Handedness Inventory. This is inconsistent with studies that have found a higher frequency of left-handedness among dyslexics than in the general population (Geschwind & Behan, 1982). Further, our results suggest that dyslexics' impairment in statistical learning is independent of handedness, since the impairment held after controlling for scores on the

Edinburgh Handedness Inventory. This indicates that the fact that atypical brain lateralization is associated with both left-handedness and dyslexia (Brandler & Paracchini, 2014) and that statistical learning is dependent on certain lateralized brain areas (Turk-Brown et al., 2009) does not play a role in our study.

Our results are important in the light of the various difficulties individuals with dyslexia face and the effects of these difficulties on society (Al-Lamki, 2012; Dahle et al., 2011). Advancement in the knowledge of dyslexia's causes is necessary for accurate diagnosis and treatment of dyslexia. Since studies suggest that dyslexia is underdiagnosed (Arzubi & Martin, 2005), it seems that a more effective diagnostic tool for dyslexia is needed. If further studies support our finding that dyslexia can be partially traced to a deficit in statistical learning, it may possibly be useful to incorporate a measure of statistical learning ability into the dyslexia diagnosing process, and perhaps even include tasks that train and improve statistical learning in the treatment of dyslexia. Using a statistical learning measure could be particularly beneficial for diagnosing dyslexia in people whose first language has a shallow orthography, such as Icelandic, since most diagnostic tools for dyslexia are developed in places in which the first language has an opaque orthography, such as English (Bjornsdottir et al., 2013). It is possible that diagnostic tools for dyslexia that are developed in places with opaque-orthography languages, for which phonological awareness is more important for reading skills, do not work as well in places with a shallow-orthography language, for which phonological awareness matters less and visual processing possibly matters more for reading skills than in opaque-orthography languages (Bjornsdottir et al., 2013; Ziegler et al., 2010).

There are a few potential drawbacks of our study that should be considered in future research. First, there is some evidence that the statistical learning task as a whole may have been too long. The statistical learning task in our study was longer in duration compared to previous studies using statistical learning tasks on which our task was modeled (e.g. Arciuli & Simpson, 2012b; Turk-Browne et al., 2009). In addition, participants' percentage correct responding in the two-alternative forced-choice familiarity test was higher in our study compared to previous studies. In the current study, the average correct for all participants as a whole was little over 72%, compared to average accurate responding in the 50-60% range in previous studies (notably, Arciuli & Simpson, 2012b; Turk-Browne et al., 2009). The reason we decided to use a longer statistical test than is normally done is that it is hard if not impossible to differentiate between two groups if the average accurate responding is too close to chance performance. The relatively high correct responding in our study indicates that becaue of the test's length, at least some of the participants may have learned the pair structure explicitly. However, participants' replies to questions asked at the end of the study indicate that few participants noticed one or more base pairs. As a result, this does not pose a significant problem in our study, but should be considered in future research.

Second, since performance on the two-alternative forced-choice familiarity test was quite heterogeneous in both the dyslexic and typical reader group, in future studies it would perhaps be advisable to administer the same version of the test for all participants, so that the same shapes would go together in base and foil pairs and in the same order for all participants. This would likely minimize individual differences, and therefore possibly yield a clearer difference between dyslexics and typical readers in statistical learning performance. Third, since former ADHD diagnoses were not consistent with the ADHD screening test, and since most ADHD diagnoses are performed in childhood and childhood symptoms do not necessarily last until adulthood (Nolen-Hoeksema, 2014), in future studies it would probably be more clear-cut to exclude people with ADHD diagnoses from participating and only use the ADHD screening test to indicate ADHD in participants.

In addition, Icelandic, the primary language of our participants, has a shallow orthography (Sigurdardottir et al., 2015). Since the importance of phonological awareness for reading performance is considered to be greater for languages with opaque than shallow orthographies (Ziegler et al., 2010), visual processing skills (e.g. visual statistical learning abilities) may be less important for reading in languages with opaque orthographies, than in languages with shallow orthographie. In addition, the exact type of visual processing that is most important for reading may depend on the language's orthography and structure (Sigurdardottir et al., 2015). Future studies need to establish whether our results hold for dyslexics whose primary languages have opaque orthographies.

Furthermore, even though our results suggest that dyslexics generally have poorer statistical learning abilities compared to typical readers, we do not know if these impairments contribute to dyslexia or if they are a consequence of dyslexia. Studies show that dyslexics read considerably less, on average, compared to typical readers (Siegel, 2006). They therefore have less experience with the orthographic and morphological regularities of written words, which could possibly cause this deficit in statistical learning. To find out which is the case, it may be advisable to perform a study with young children who have not yet learned to read, and compare statistical learning abilities in children at high risk for dyslexia (e.g. genetic risk) with statistical learning abilities in children at little or no risk for dyslexia.

Conclusions

Statistical learning is thought to be crucial for a wide range of perceptual and cognitive processes. There is growing evidence that learning statistical regularities underlies reading, and recent studies suggest that a higher ability for statistical learning is related to a higher reading ability in the general population. Our results show that dyslexics have poorer statistical learning capacity compared to typical readers, suggesting that dyslexia can be partially traced to a deficit in statistical learning. Furthermore, dyslexia's association with statistical learning cannot be explained by differences between dyslexics and typical readers in intelligence, ADHD, object recognition abilities, or handedness.

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