The specificity of the visual deficits of dyslexic readers

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Lokaverkefni til B.S. gráðu
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HÁSKÓLI ÍSLANDS

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Lokaverkefni til B.S. gráðu í sálfræði
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Preface

This paper was written under the guidance of Dr. Heiða María Sigurðardóttir and Dr. Árni Kristjánsson who gave us the invaluable opportunity to experience the inspiring and stimulating (but at the same time challenging) world of experimental psychology. We are immensely grateful for Dr. Heiða María's mentoring and guidance throughout the semester. Writing this thesis took hard work and dedication but without Heiða María this paper would never have become a reality.

Objective: The objective of the current study was tripartite; first, to establish the impaired face processing of dyslexic readers in a large sample; secondly, to assess whether the hypothesized perceptual impairment of dyslexic readers is specific to higher order visual processing; lastly, to determine whether the proposed higher level visual processing deficits of dyslexic readers extend to the perception of novel objects. Research suggests that dyslexic readers are impaired at the perception of faces and other complex objects. Therefore, it would be expected that dyslexia might stem from a deficit within the higher visual system. **Method**: 32 diagnosed dyslexic readers (*M*=26.3 years) and 32 matched typical readers *(M*=26.1 years) participated in the study. Performance was measured on the FYS-test, which involves three separate discrimination tasks, each with different stimuli: faces (F), novel computer-generated objects called YUFOs (Y) and scrambled faces (S). **Results:** Dyslexic readers have impaired face perception compared to typical readers, but do not have complications with perceiving novel objects or scrambled faces. **Conclusion:** Reading difficulties in dyslexia might partially be caused by deficits in higher level visual processing, specifically in the perception of familiar objects such as words and faces.

Developmental dyslexia

Developmental dyslexia is a specific learning disorder characterized by reading impairments, involving slow reading, poor word reading accuracy, complications with spelling and poor reading comprehension (American Psychiatric Association, 2013). An individual is considered to be dyslexic if his reading ability is significantly below what is expected from his age, schooling, motivation and intelligence (American Psychiatric Association, 2013, Blau et al., 2010; Ahissar, 2007; Serrano & Defior, 2008). Dyslexia is perhaps the most frequent learning disorder, with a prevalence rate ranging from 5-17.5 percent (Roeske et al., 2011; Shaywitz, 1998). Approximately 10 percent of Icelandic children have reading impairments, despite adequate education (Bjornsdóttir et al., 2013). However, due to the short history of official diagnosis of learning disorders in Iceland, dyslexia is probably underdiagnosed among adults. Therefore, no reliable data exists on the prevalence of dyslexia in the Icelandic population (Bjornsdóttir et al., 2013).

Despite decades of research on dyslexia, its underlying cognitive and biological causes are still debated (Ramus et al., 2003). A number of theories have been proposed but according to well-known theories dyslexia is a language disorder (Catts, 1989; Ramus et al., 2003) concerning an impairment in phonological processing (Díaz, Hintz, Kiebel & von Kriegstein, 2012; Pennington, Van Orden, Smith, Green, & Haith, 1990). The phonological theory of dyslexia postulates that the reading disorder is caused by a cognitive deficit specific to phonology, i.e. the mental representation and manipulation of speech sounds (Ramus et al., 2003, Ramus, 2004). The phonological impairment is considered to cause difficulty in learning and handling the link between letters and their corresponding speech sounds, also known as grapheme-phoneme correspondence (Ramus, 2004). Learning this grapheme-phoneme correspondence is considered necessary for learning to read an alphabetic system, consequently making it difficult for dyslexic readers to achieve satisfactory reading skills (Ramus, 2004). The theory is supported by strong and convergent evidence of dyslexic readers' poor performance on tests which measure their phonological awareness (the awareness that words can be broken down into smaller units of sound and the ability to manipulate these sounds consciously) and ability to decode nonsense words (segmenting speech into its underlying phonological elements and linking each letter to its corresponding sound) (Vellutino, Fletcher, Snowling & Scanlon, 2004). The most compelling evidence for the causal role of phonological skill deficiencies in dyslexia comes from intervention studies, designed to improve phonological awareness and letter-sound mapping, in which the intervention improves spelling, word identification, and reading ability (Shaywitz & Shaywitz, 2005; Vellutino et al., 2004).

Although the phonological deficits of dyslexia are evident, researchers debate whether they are a cause or consequence of the disorder (Ramus et al., 2003; Ramus 2004). Challengers of the phonological theory maintain that the phonological impairment is just one aspect of a more extensive disorder, originating in general motor, sensory, or learning processes (Ramus et al., 2003). Further indication of the ambiguity of the role of phonological deficits in dyslexia stem from the observation that not all dyslexic readers show phonological deficits, and thus the same individual can perform adequately on a phonological test but lack the ability to read fluently (Valdois, Bosse, & Tainturier, 2004). Furthermore, the orthographic depth of a language determines the importance of phonological factors in reading (Ziegler et al., 2010). Phonological awareness plays a larger role in languages such as English, where the orthography is opaque than in languages when the orthography is more transparent (Share, 2008; Ziegler et al., 2010). Therefore, English-based research could possibly be overestimating the importance of the phonological awareness in dyslexia (Ziegler et al., 2010). Consequently, researchers have attempted to discern alternative factors that might contribute to dyslexia.

Early theories of visual impairments in dyslexia

The idea that impairments within the visual system might play a role in dyslexia was introduced back in the late 19th century (Morgan, 1896). One of the earliest hypotheses of visual processing deficits in dyslexia, the magnocellular hypothesis, proposes that the cause of dyslexia lies in an impairment of the magnocellular system (Lassus-Sangosse, N'guyen-Morel & Valdois, 2008). The magnocellular system sends information about low spatial frequencies and movement to the striate cortex (Goodale & Milner, 1992). The information is then forwarded primarily to the dorsal visual stream, which is involved in processing visual spatial information, movement and information about how to interact with objects (James, Humphrey, Gati, Menon & Goodale, 2002; Goodale & Milner, 1992; Valyear, Culham, Sharif, Westwood & Goodale, 2006). The parvocellular pathway, on the other hand, delivers information about high spatial frequencies through the striate cortex onwards to the ventral visual stream (Goodale & Milner, 1992). The ventral stream is often referred to as the *what* pathway, as it is crucial for the recognition and perception of objects (James et al., 2002; Ungerleider & Haxby, 1994; Valyear et al., 2006).

Since reading almost surely requires the ability to recognise fine-grained patterns in script, the aforementioned theory has been criticised for limiting the problem to the magnocellular stream (Skottun & Skoyles, 2006; for a review see Vidyasagar, 1999). If dyslexia is in fact rooted in impairments of the magnocellular stream, the perceptual deficits of dyslexic readers should be limited to stimuli of low spatial frequencies. But dyslexic readers have problems with stimuli of all spatial frequencies (Ben-Yehudah & Ahissar, 2004; Ramus et al., 2003). The theory does therefore not fully explain how perceptual deficits contribute to dyslexia. Nonetheless, the link between dyslexia and visual perception is gaining increased attention. Converging evidence of the interdependency of the mechanisms of face and word perception has sparked interest in whether dyslexic readers show abnormal face processing (Behrmann & Plaut, 2013; Dehaene & Cohen, 2011; Dundas et al., 2013; Starrfelt, Klargaard, Petersen & Gerlach, 2016). Before discussing how dyslexic readers' face processing might be impaired, we will first consider the basic features of the processing of words and faces.

The interdependence of perception of words and faces

The neural substrates of reading and face perception

Face recognition is just as vital in our everyday interaction as it was for our primate ancestors (Kanwisher & Moscovitch, 2000; Parr, 2011). Even during the first months of life, infants show a preference for faces (Valenza, Simion, Cassia & Umiltà, 1996), thus making face perception one of the most practiced visual skills (Bilalić, Langner, Ulrich & Grodd, 2011). Yet face perception is a computationally demanding task, and advantages to having specialized neural hardware for face perception could be substantial (Kanwisher & Yovel, 2006). The fusiform face area (FFA) is a region located in the lateral part of the fusiform gyrus in the temporal lobe that responds at least twice as strongly to faces as to various types of non-face stimuli (Kanwisher et al., 1997; McCarthy, Puce, Gore, & Allison, 1997). The area's importance in facial recognition has been consistently supported by functional imaging studies (Kanwisher, McDermott & Chun, 1997; McCarthy, et al., 1997) as well as lesion studies (Barton, Press, Keenan & O'Connor, 2002; Bauer, 2006). A lesion to the right FFA causes prosopagnosia, a condition characterized by problems with identifying faces (Bauer, 2006). Although face-processing shows right hemispheric dominance (Yovel & Belin, 2013; Yovel, Tambini & Brandman, 2008) face processing also takes place in the left fusiform gyrus of the left hemisphere, in the left FFA (Harris & Aguirre, 2010).

Functional brain imaging studies have identified a brain area located close to the FFA in the left inferior occipitotemporal cortex, that might be involved in identifying words and letters (Bentin, Mouchetant-Rostaing, Giard, Echallier, Pernier, 1999; Dehaene, Le Clec'H, Poline, Le Bihan & Cohen, 2002). The area, most often referred to as the visual word form area (VWFA) (Cohen et al., 2002) is highly responsive to printed words as well as pseudowords displayed to skilled, non-dyslexic readers (Dehaene et al., 2002). Lesions of the VWFA and surrounding tissue often result in a reading disorder called pure alexia (Pflugshaupt et al., 2009; Cohen et al, 2004). Pure alexia is characterized by reading difficulties, but writing skills and language comprehension remain intact (Montant, & Behrmann, 2000; Cohen et al., 2004; Pflugshaupt et al., 2009;). Although patients with pure alexia can recognize single letters, their reading is based on a slow letter-by-letter method; hence pure alexia is often referred to as letter-by letter dyslexia (Montant & Behrmann, 2000; Fiset et. al, 2005). Electrical stimulation near the VWFA can induce symptoms of pure alexia (Mani et al., 2008).

Words and faces have long been considered to be processed by independent neural mechanism – faces in the FFA (Kanwisher et al., 1997) but words in the VWFA (Cohen et al., 2000; Grill-Spector & Weiner, 2014). Neurological case studies suggest a double dissociation for word and face processing mechanisms (Farah, 1991), since the perceptual problems of pure alexia seem specific to word processing, leaving face perception relatively unaffected, opposed to acquired prosopagnosia where face recognition is impaired while reading capacity remains intact (Farah, 1991; Rivest, Moscovitch & Black, 2009; Tsapkini, & Rapp, 2010). However, the double dissociation of face processing and reading has been contradicted by recent studies, showing that patients with pure alexia are impaired in the perception of not only script, but also faces and other complex objects (Dundas, Behrmann & Plaut, 2014; Farah & Wallace, 1991). In addition, converging evidence suggests that the recognition of words and faces are indeed linked (Behrmann & Plaut, 2013; Dehaene & Cohen et al., 2011; Dundas, Plaut, & Behrmann, 2013; Starrfelt et al., 2016).

Those findings lead to the speculation that visual factors could also be one facet of developmental dyslexia (Sigurdardottir, Ívarsson, Kristinsdóttir & Kristjánsson, 2015). Further support for that idea comes from an extensive meta-analysis that strongly suggests that the same area that is lesioned in pure alexia (the VWFA and surrounding tissue in the left fusiform gyrus) is hypoactive in both dyslexic adults and children (Richlan, Kronbichler, & Wimmer, 2011). In addition, structural abnormalities have been reported in the cerebral cortex of the left fusiform gyrus of children with dyslexia (Ma et al., 2015). They have increased cortical thickness, possibly resulting from inefficient neural pruning (Ma et al., 2015). This holds even for dyslexic children that have reading scores in the normal range (as a consequence of special remediation training). The cortical abnormalities of the left fusiform gyrus are therefore an ingrained feature of dyslexia that is not merely a result of a lack of reading experience (Ma et al., 2015).

Although the VWFA is expected to be primarily involved in word processing, it responds to other visual objects such as faces (Dehaene et al., 2010) and meaningful symbols (Reinke, Fernandes, Schwindt, O'Craven & Grady, 2008). In addition, object- and word-selective regions partially overlap and extend posteriorly to face-selective region (Dehaene et al., 2010). It follows that dyslexic readers might show processing deficits not only for words but also faces (Sigurdardottir et al., 2015).

The impact of literacy on face processing

Even though the written language is perhaps as crucial for everyday interaction as face perception, it was not invented until relatively late in the history of the human species. The period people have been reading is presumably too short for natural selection of a specific reading brain mechanism to occur (Dehaene & Cohen, 2011; Szwed et al., 2011). Hence, it is likely that literacy acquisition requires some recycling of pre-existing brain areas (Dehaene & Cohen, 2011) that are capable of the fast high acuity parallel processing necessary for skilled reading (Szwed et al., 2011). The VWFA is located in an area of the ventral visual cortex which has been suggested to possess certain properties that make it especially suitable for word processing (Dehaene & Cohen, 2011), such as an initial preference for processing foveal stimuli (Hasson, Levy, Behrmann, Hendler & Malach, 2002) and recognizing line junctions (Szwed et al., 2011). It has therefore been proposed that neurons belonging to the VWFA are "recycled" as reading processes take over (Dehaene et al., 2010; Glezer, Kim, Rule, Jiang & Riesenhuber, 2015).

Words and faces both require processing of high acuity visual information (Hasson et al., 2002) and are considered to compete for representational space in the fusiform area in both hemispheres (Dehaene & Cohen, 2011; Dundas et al., 2013). Since language processing is left lateralized in most individuals, visual word representation is presumably pressured to be left lateralized (Gabay, Dundas, Plaut, & Behrmann, unpublished; Dehaene & Cohen, 2011; Dundas et al., 2013; Ventura et al., 2013). Face lateralization develops later than word lateralization and depends on reading skills, suggesting that visual word lateralization drives the lateralization of faces (Dehaene, Dehaene-Lambertz & Hertz-Pannier, 2002; Dundas et al., 2013, 2014). fMRI studies have shown that as reading skills increase, the VWFA becomes more responsive to written strings (relative to illiterates), but responsiveness to faces decreases. On the contrary, the right FFA becomes more sensitive to faces with increased literacy and apparently takes over some of the former roles of the corresponding left fusiform gyrus region to a certain degree (Dehaene et al., 2010; Dundas et al., 2013, 2014; Monzalvo, Fluss, Billard, Dehaene & Dehaene-Lambertz, 2012; Ventura et al., 2013).

The face perception literature has laid great emphasis on the role of holistic processing in face recognition (for a review Richler & Gauthier, 2014). In holistic processing – also called global, configural, or relational – the face is perceived as a whole, making it more difficult to process its individual features (Maurer, Le Grand, & Mondloch, 2002; on the ambiguity of the construct: Rezlescu, Susilo, & Caramazza, 2015; Richler, Palmeri, & Gauthier, 2012). In contrast in feature-based processing – also called analytic, piecemeal, componential, or part-based processing – the parts of the face are analysed (Maurer et al., 2002). The right hemisphere, including the right FFA, is believed to be an important area for holistic processing (Liu, Harris & Kanwisher, 2009; Yovel and Kanwisher, 2005) whereas the fusiform gyrus of the left hemisphere is more specialized in feature based processing (Bourne, Vladeanu, M., & Hole., 2009; Harris & Aguirre, 2010; Rossion et al., 2000). Because of this hemispheric dominance for each type of processing, it seems plausible that the lateralization of face and word processing has some implication for the use of particular face perception strategies (Ventura et al., 2013).

Ventura et al. (2013) tested whether reading ability affects holistic face processing. Their result indicate that illiterates use holistic processing of houses and faces even when it is detrimental to performance. Literates can switch to feature-based processing when the tasks demand it, suggesting that learning to read increases flexibility in the use of otherwise automatic holistic processing (Ventura et al., 2013). The researchers explained the results with the notion that when one acquires reading skills, the left fusiform gyrus is trained in feature-based processing. The fusiform gyrus of individuals who never acquire literacy will not be trained in the same way. Literates have the opportunity to use holistic processing in the right FFA and feature-based processing in the left fusiform gyrus when perceiving faces, while non-readers have to rely solely on holistic processing (Ventura et al., 2013). Furthermore, reading acquisition may cause a rearrangement of how areas adjacent to the VWFA respond to faces, houses and objects (Dehaene et al., 2010), similar to how visual expertise for non-face objects can affect face processing (Gauthier, Curran, Curby, & Collins, 2003).

The evidence for the co-dependency of word and face processing might have some implications for dyslexic readers. The left fusiform gyrus, which has been shown to be hypoactive in dyslexic readers, seems to be not only involved in visual perception of words, but also faces and perhaps non-face within-category object discrimination (Dehaene et al., 2010). Thus, dyslexic individuals might have difficulty with processing faces, and perhaps other objects as well.

Face perception impairments of dyslexia

There are some discrepancies in the literature on the link between developmental dyslexia and facial perception (Gabay et al., unpublished). In a study carried out by Tarkiainen, Helenius and Salmelin (2003), individuals with developmental dyslexia needed longer time than controls to estimate the resemblance of both faces and geometrical shapes. Dyslexic subjects were also less accurate than controls on a facial recognition task (Tarkiainen et al., 2003). Furthermore, individuals with dyslexia showed normal face-specific activation at 150 ms after stimulus onset, indicating dyslexia does not affect the occipito-temporal encoding of faces (Tarkiainen et al., 2003).

Monzalvo et al., (2012) examined the brain activity of dyslexic children compared to typically developing children on various visual search tasks. Dyslexic children showed less activation than the typical readers in the VWFA when words were presented. However, the left-hemispheric activation (in the VWFA) of the two groups did not differ substantially when faces were presented. Interestingly dyslexic children showed less activation in the right FFA in response to faces compared to controls (Monzalvo et al., 2012). Thus, the normal readers showed greater right-lateralization in response to faces than the dyslexic readers, consistent with findings showing that literacy drives the representational competition of faces in the left fusiform and increases the responsiveness of the right fusiform gyrus to faces (Dehaene et al., 2010).

However, a number of studies report no differences in face processing in individuals with dyslexia and controls (Brachacki, Fawcett, & Nicolson, 1995; Rüsseler, Johannes & Münte; Smith-Spark & Moore, 2003) suggesting a double dissociation between face processing and reading. For instance, Rüsseler, et al. (2003) found no differences between recognition of unfamiliar faces in adult dyslexics and controls. These contradictory results might stem from varying task difficulties. Gabay et al. (unpublished manuscript) manipulated the perceptual complexity of a face perception task. Differences between individuals with dyslexia and typical readers emerged only in the perceptually demanding tasks, but not in the easier conditions. In another experiment reported in Gabay et al. (unpublished manuscript) dyslexic and control participants solved a face task, similar to the one used in the current study, where three faces were presented simultaneously and the participants had to match to sample. Overall, dyslexic readers were slower to respond than controls, but no accuracy differences were found. Additionally, the dyslexic readers showed greater cost in response times than controls when the task required matching the target and the choice face over orientation.

Sigurdardottir et al. (2015) tested the face recognition skills of dyslexic readers compared to matched controls. Dyslexic readers were less accurate in general face recognition than non-dyslexic readers, but the groups did not differ in holistic processing. This led the authors to propose that face processing deficits of dyslexic readers could be explained by impaired part-based face processing. Likewise, Gabay et al. (2015) found no differences between dyslexic and typical readers' performance on a face inversion task, a common measure of holistic processing. This effect could be related to the hypoactivity of the left fusiform gyrus in dyslexic readers, since this area is likely involved in part-based processing, while the right fusiform gyrus is more important for holistic processing (Liu et al., 2009; Yovel and Kanwisher, 2005).

To summarize, although some research suggests the face processing abilities of dyslexic readers do not deviate from typical readers (Brachacki et al. 1994; Rüsseler et al., 2003; Smith-Spark & Moore, 2009) a growing body of research finds that dyslexic readers are impaired in face processing (Gabay et al. 2015; Sigurdardottir et al., 2015; Tarkiainen et al., 2003). Further support comes from evidence that the mechanisms of face and word perception are interdependent (Behrmann & Plaut, 2013; Dehaene & Cohen, 2011; Dundas, et al., 2013; Starrfelt et al., 2016) and reported hypoactivity of the fusiform gyrus of dyslexic readers (Monzalvo et al. 2012; Richlan et al. 2011). Thus, dyslexia might not be limited to problems with processing words, but could be extended to the processing of faces as well. So far, few studies have investigated general object perception abilities of dyslexic readers, and none have investigated the perception of novel yet realistic-looking objects with which people have no previous experience.

Expertise in face and object perception

Words and faces are comparable in the respect that humans usually have great experience with perceiving both classes of stimuli (McCandliss, Cohen & Dehaene, 2003). Since dyslexic readers potentially show complications in perceiving both words and faces, it might be possible that the reading difficulties of dyslexic readers could be partially traced to difficulties with perceiving objects of expertise.

Perhaps the most controversial topic in the field of higher level visual perception involves the degree of specificity of the perceptual mechanism involved in face processing (Rossion, Collins, Goffaux & Curran, 2007). Kanwisher et. al (1997) proposed that the FFA is a functionally specific module devoted solely to face recognition. In contrast to this specificity hypothesis, the expertise hypothesis maintains that the FFA is specialized for the individuation of objects that share similar perceptual features, i.e. subordinate-level classification (Gauthier, Skudlarski, Gore & Anderson, 2000; Gauthier, Tarr, Anderson, Skudlarski, Gore, 1999). The right FFA responds more strongly to non-face objects of visual expertise than to novel stimuli (Gauthier et al., 2000; see opposing views: Kanwisher & Yovel, 2006). This has been shown for several domains of expertise, including birds, butterflies, cars, chessboards and even artificial object classes (Bilalić et al., 2011; McGugin, Van Gulick, Tamber-Rosenau, Ross, & Gauthier, 2014; Gauthier et al., 2000; Gauthier et al., 1999; Xu, 2005). These findings have fostered a debate about whether the right FFA is specialized for expertise-specific visual processing rather than face-specific processing (Xu, 2005). Interestingly, studies using ERPs (Rossion, Gauthier, Goffaux, Tarr & Crommelinck, 2002) or MEG (Liu, Higuchi, Marantz, & Kanwisher, 2000) have found a stronger effect of expertise in the left hemisphere; in contrasts to fMRI studies.

As experience with non-face object categories (e.g. cars) grows, the correlation between face recognition and the recognition of objects of expertise increases (Gauthier et al, 2014; Wang, Gauthier and Cottrell, 2016). In addition, the visual processing of the category of expertise starts to resemble visual processing distinctive of face processing – holistic processing (Bukach, Phillips, & Gauthier, 2010). For example, when people gain expertise in chess, they begin exhibiting increased holistic processing of chess boards (Boggan, Bartlett, & Krawczyk, 2012) and show higher FFA BOLD activity to chess positions than novices (Bilalić et al., 2011). Gauthier, Williams, Tarr and Tanaka (1998) trained participants to discriminate between visually similar novel objects called Greebles. Training resulted in better performance, but more importantly, participants showed an increase in visual processing characteristic of face perception; holistic and configural processing. Those effects generalized to new Greebles in the category of visual expertise (Gauthier, et al., 1998). It should be noted that plasticity in the visual system is not only influenced by stimulus type but also the type of experience. For instance, tasks demanding subordinate-level discrimination of visually similar objects result in increased holistic processing of the objects, while basic level classification of the same objects does not (Wong, Palmeri, & Gauthier, 2009; Wong et al., 2011).

Wong et al. (2011) showed that similar to other visual objects, the type of processing used to recognise letters in words depends on experience. Feature-based processing of letters in words, characterised by letter by letter processing in a left to right sequence, is a more prominent feature of reading in beginners (Farah, Wilson, Drain & Tanaka, 1998; Martelli, Majaj & Pelli, 2005; Whitney, 2001). As reading experience grows, the visual processing of words becomes increasingly holistic as neurons become selective to whole words, enabling quick recognition of commonly-perceived words (Glezer et al., 2015; Tydgat & Grainger, 2009). Holistic processing is used more by native than second-language readers and for real words rather than pseudowords in native readers (Wong et al., 2011).

As mentioned, dysfunctional areas in dyslexic readers might overlap with other regions of the left fusiform gyrus, such as the FFA, making it plausible that dyslexic readers might show abnormal processing of faces and objects that require within-category individuation. Furthermore, if the FFA is an area of expertise (Gauthier et al., 2000), this could mean that dyslexic readers are not able to gain expertise in complex object perception to the same extent as typical readers.

Object perception abilities of dyslexia

To date, few studies have investigated the object perception abilities of dyslexic readers. Sigurdardottir et al. (2015) tested the performance of dyslexic readers on a within-category object recognition task (the Vanderbilt Expertise Test) using five object categories: birds, butterflies, cars, houses, and planes. The dyslexic readers performed considerably worse than typical readers. Research suggests recognition of nonverbal symbolic things such as traffic signs might be impaired in dyslexia. Brachacki et al. (1995) showed that adults with dyslexia display impaired ability in discriminating between real and fake traffic signs, compared to controls (1995). Moreover, dyslexic readers' knowledge of traffic signs seemed to improve very little from driving experience. On the other hand, there was a significant correlation between traffic sign recognition and driving experience for the controls. Authors interpreted these results as indicating that dyslexic readers have a deficit in implicit learning (Brachacki et al., 1995). Araújo et al. (2011) showed that dyslexic readers have problems with integrating visual information in long-term memory and an impaired coding and decoding ability with representations of two-dimensional visual surface features.

Yet, not all results find that dyslexic readers differ from typical readers in object discrimination. Dyslexic readers performed similarly to controls on a car recognition task (Gabay, unpublished manuscript). However, they did not take participants' level of expertise into account, which might possibly affect differences in discrimination abilities (Gauthier et al., 2014). Monzalvo et al. (2012) examined the brain activation of dyslexic children compared to typically developing children. The dyslexic children showed normal brain activation to houses (in the Parahippocampal Place Area) and checkerboards. It is worth noting that in Monzalvo et al. (2012) the activation was measured while participants solved a visual search task, finding a star amongst distractor stimuli, in this case houses. Therefore, the task did not require within-category discrimination and did perhaps therefore not evoke responses in areas that are hypoactive in dyslexic individuals, such as the fusiform gyrus. Taken together, data are scarce on object processing skills of dyslexic readers. To the best of our knowledge, no studies have addressed whether the visual deficits of dyslexic readers extend to novel yet realistic objects.

The current study

The current study has three main goals; First, to establish the impaired face processing of dyslexic readers in a large sample. The second goal is to establish the specificity of the hypothesized perceptual impairment of dyslexic readers; whether it is specific to higher order visual processing. The third goal is to assess whether the proposed higher level visual processing deficits of dyslexic readers extend to the perception of novel objects. An additional goal of the current study was a pilot testing of a measure of silent reading speed.

Method

Participants

70 native Icelandic speakers participated in the study and were assigned to one of two groups: dyslexic readers (experimental group) and typical readers (control group). Two participants were immediately excluded: one fell asleep during the experiment and another was assigned to the typical reader group but acknowledged being diagnosed with dyslexic dysgraphia during testing. Matched typical readers were not found for two participants of the dyslexic groups, so their data was also excluded. Lastly, one dyslexic participant and his matched control were excluded as the dyslexic participant's performance on the FYS-test was

unusually low (see Data analysis section). This left 32 dyslexic readers and 32 typical readers.

Participants in the experimental group were 32 individuals with a prior diagnosis of dyslexia (21 women and 11 men). For every dyslexic participant, there was a matched non-dyslexic participant of the same gender and age (+/- 5 years), with a comparable education (completed the first, second, third, or fourth stage of the Icelandic schooling system, which corresponds more or less to high school, gymnasium, college, and university, respectively). Requirements for participation were normal hearing and normal or corrected vision with glasses or contacts. Furthermore, participants were only included if they were not diagnosed with autistic spectrum disorder, as individuals with autistic spectrum disorder are commonly assumed to show impaired face recognition abilities (e.g. Boucher & Lewis, 1992; Schultz; 2005; for review of conflicting findings see Jemel, Mottron, & Dawson, 2006).

The age of the dyslexic participants ranged from 18 to 49, with the mean age 26.3 years. The mean age for typical readers was 26.1, ranging from 18 to 52 years. In both groups fifteen individuals had completed the first level of schooling, fourteen had completed the second level of schooling, two had completed the third level and one had completed the fourth level of schooling. The participants were volunteers and were not paid for their participation. However, participants were offered to take part in a lottery in which five were randomly selected to receive a 10.000 kr. (approx. US$80) gift voucher.

Test material and procedure

The study was approved by the Icelandic Science Review Board and reported to the Icelandic Data Protection Authority. The study took place in a well-lit, quiet room. At the start of their experimental session, participants were given the choice of reading the consent form themselves or hearing it read aloud before giving their informed consent. All participants answered questions regarding prior diagnosis (e.g. autism, ADHD and dyslexia), and their history of medication (e.g. Ritalin, Concerta). The following tests and measures were then administered: Self-reported experience, Face-YUFO-Scrambled test, Face/No face test, Questionnaires of ADHD, Adult Reading History Questionnaire, Reading in silence, IS-FORM reading test, IS-PSEUDO reading test. The results for the self-reported experience test were part of a separate pilot study and are not analyzed here.

Face-YUFO-Scrambled test (FYS-test).

Test design and procedure. The FYS-test was specifically created for the current study. The test consisted of three discrimination tasks, each with different stimuli: faces (F), novel computer-generated objects called YUFOs (Y) (copyright Mike Tarr, 2006: http://wiki.cnbc.cmu.edu/Novel_Objects), and scrambled faces (S), see *figure 1*. The test began with six practice trials with pre-recorded instructions, followed by four blocks of each task. A block consisted of 48 trials, so participants completed a total of 192 trials per task, 576 trials altogether. On each trial, three stimuli were presented simultaneously (e.g. three faces). The goal of each trial was to match to sample. The sample stimulus was presented in the centre of the screen with two comparison stimuli on each side – one match and one non-match. The two comparison stimuli were positioned approximately 9 degrees of visual angle to the left and right of centre (measured from the centre of the screen towards the center of the stimuli). Participants indicated the location of the match by pressing a “left” or “right” button marked with stickers on the keyboard. Presentation time was unlimited; the stimuli stayed on-screen until the participants responded. The intertrial interval was 200 milliseconds from button press.

The non-match stimuli for all the trials were selected at random when creating the trials but the non-match stimuli remained the same for all the participants. Therefore, all participants went through the same trials (i.e. compared the same stimuli), but in a different order. However, whether the match stimulus appeared to the left or to the right was randomized for each matched participant pair. Trial order was randomized for each dyslexic/typical reader pair; this was done separately for face, YUFO, and scrambled trials. A dyslexic reader therefore saw the stimuli in the same randomized order as his or her matched typical reader. Trials within the three tasks were further divided into four blocks. Block order was also randomized for each participant pair, with the constraint that a block of each type (F, Y, and S) had to be shown before any other block type could be selected (e.g. YFSFYS... but never YFY…). Blocks were followed by pauses that lasted until the participant pressed either the left or right button.

Participants were instructed to respond as fast as they could while keeping errors at minimum. They were also asked to inform the researchers once they finished the first block of trials and reached the first pause. Once they had reached the first pause the experimenters asked if everything was clear and if they had any questions. They also reminded participants to respond as fast as they could while keeping errors at minimum. After they had completed the test the participants were asked what kind of strategy they had used to distinguish between the pictures. Both accuracy and response times were measured.

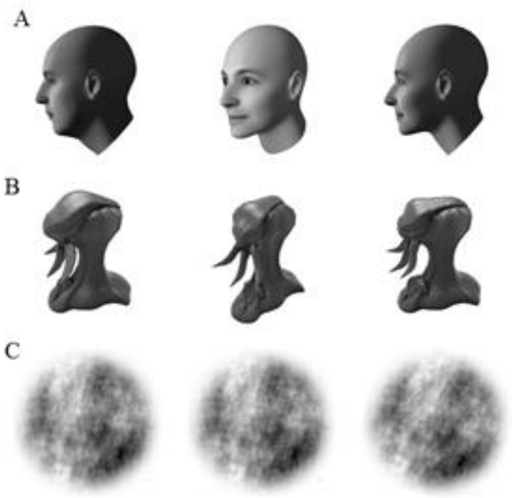

Figure 1 An example of the stimuli used in each task of the FYS-test. A) The face task: Here the right face is the same as the sample stimulus in the middle. B) YUFOs: here the right stimulus matches the sample. C) Scrambled faces: the three images are all the same except for the tilt; the tilt of the left stimulus matches the sample.

FYS-test stimuli. The stimuli used in the FYS-test were of three kinds: 48 novel computer generated objects (YUFOs), 48 faces, and 48 scrambled versions of the faces. The stimuli were presented on a CRT monitor (85 Hz, resolution 1024x768) using PsychoPy (Peirce, 2007).

Face stimuli. The face stimuli were rendered images of three-dimensional human faces created with the program FaceGen (www.facegen.com). The program was used to make 48 random symmetric Caucasian faces. Importantly, the texture cues of all faces were identical, so participants had to rely on shape cues only. The size of the face stimuli was approximately 5 degrees of visual angle. The faces could be displayed from five different viewpoints: 0°, ± 45° or ±90°. Each face appeared four times in total as a sample in the experiment, with either 45° or -45° viewpoint. The two comparison stimuli were always displayed from the same viewpoint, which could either be 0° or ±90°. Each face sample therefore appeared two times in a -45° viewpoint (thereof one time with match/non-match with -90° viewpoint and one time with 0° match/non-match) and two times in 45° viewpoint (match/non-match with 90° or 0° viewpoint). Consequently, the viewpoint difference between the sample and comparison stimuli was always 45°.

YUFO stimuli. The novel "alien" objects are called Yu's Un-Facelike Objects or YUFOs (copyright Mike Tarr, 2006: http://wiki.cnbc.cmu.edu/Novel_Objects). The original images were downloaded from the CNBC wiki website (CNBC wiki, 2015). The images were changed to grayscale for the current study. In addition, the background was removed. YUFOs are visually similar three-dimensional objects. YUFOs are of different categories or families, consisting of individuals of two “genders” (Tarr, 2006). Objects within each family have the same basic structure. Subtle characteristics distinguish each individual YUFO, such as differences in the shape of the "head" and the "body" (Gauthier, James, Curby & Tarr, 2003). In the FYS-test, sample/match and non-match YUFOs were always of the same family and gender.

48 YUFO ‘individuals’ were used in the experiment. The size of the YUFOs stimuli was approximately 5 degrees of visual angle. Like the faces the YUFO stimuli could be displayed at five different viewpoints, facing forward (rotation 0°), or rotated either 45° or 90° to the left or right. The sample YUFO had the viewpoint of either 45° or -45° on each trial. The comparison stimuli always had the same viewpoint, which could either be 0° or ±90°. Therefore, the viewpoint difference between the sample and comparison stimuli was always 45°. All YUFOs were presented four times as a sample in the experiment; twice with viewpoint of -45° (one trial where the comparison stimuli were presented at viewpoint 0°, and the other with comparison stimuli presented at viewpoint -90°) and twice with the viewpoint of 45° (once with comparison stimuli at 0° and once with comparison stimuli at 90°).

Scrambled faces. To make the 'scrambled' stimuli, the 48 faces from the face task (shown from the -45 and 45-degree viewpoint) were scrambled in MATLAB (MathWorks). A 2-D fast Fourier transform was conducted for each face image, a random phase structure was added, and the transform was then performed. Therefore, the phase, or the position, of each spatial frequency component was randomized, but the distribution of energy (the Fourier 2-D amplitude spectrum) over orientations and spatial frequencies was retained (Honey, Kirchner & VanRullen, 2008). This scrambled face image was considered to have a 0° tilt. The scrambled faces were shown within a circular window (figure 1). The size of the scrambled faces was 5.9 degrees of visual angle.

A scrambled version of each face appeared four times in total in the experiment. On a given trial, the sample, match, and non-match stimuli were identical, except that the non-match stimulus was tilted either 10° or 15° away from the sample and match. On each trial, either the sample/match or the non-match was assigned the original 0° tilt to ensure that at least one stimulus would have the original face-like orientation. The orientation difference between the two matching stimuli and the non-match stimuli could be either ±10° or ±15°. Every scrambled face was presented on one trial with each of the four possible orientation differences.

Face/No face test. The Face/No face test was created in PsychoPy (Peirce, 2007) for this current study, using image patches provided by Assaf Harrel. The task revolved around deciding whether a small piece of an image belonged to a face or not. Small 24x24 pixel patches (approximately 0.86x0.86 degrees of visual angle) appeared on the computer screen, one at a time, and participants pressed a button depending on whether they assumed the patch belonged to a face or not. Half of the patches belonged to a face and the other half belonged to non-face stimuli. Presentation time was unlimited, so the patches stayed on screen until the participants responded. Inter-trial interval was always 200 milliseconds.

Pre-recorded instructions were read in the beginning of the test, followed by four practice trials and 50 experimental trials. Two versions of the test were used that differed in which button indicated whether the patch belonged to a face or not. Half of the matched participant pairs were instructed to press the "left button" when they assumed the patch belonged to a face but the "right button" when they thought the patch did not belong to a face. The other half was instructed to do it the other way around. The order of the patches was randomized for each matched pair so participants within each pair saw the patches in the same order.

Questionnaires of ADHD. Two self-report questionnaires of attention deficit hyperactivity disorder (ADHD) symptoms, defined by the DSM-IV, were administered (Magnússon et al., 2006). The first questionnaire was a self-report of ADHD symptoms experienced in the last six months and the second questionnaire was a self-report of ADHD symptoms experienced during childhood (age ranging from 5 to 12 years old). The total score of each questionnaire can range from 0 to 54, with higher scores indicating greater ADHD symptoms. The questionnaires are reliable and valid for screening for ADHD (Magnússon et al., 2006). The participants had a choice of hearing the questionnaires read aloud or to read themselves.

Reading abilities. Eight measures of reading abilities/dyslexia were used to verify that the two groups differed in reading abilities.

Adult Reading History Questionnaire. The Icelandic version of the ARHQ (ARHQ-Ice) was used to assess each participant's history of reading difficulties (Bjornsdottir et al., 2013). Scores range from 0 to 1, with higher scores indicating a greater history of reading difficulties; the suggested cutoff score for dyslexia is 0.43 (Bjornsdottir et al., 2013). The questionnaire has been reported highly reliable and valid for screening for dyslexia (ARHQ-Ice; Bjornsdottir et al., 2013). Again, the participants were given the choice of hearing the questionnaire read aloud or reading it themselves.

Reading in silence. A test was created to measure reading speed when reading in silence. The main purpose was to measure to what extent this measurement of silent reading speed is an indicator of out loud reading speed and to what extent it can be used to differentiate between dyslexic and typical readers. Using a test where participants read in silence has some benefits. First, it is easier to administer than a test where participants read out loud. Secondly, most people are used to reading in silence while the experience of reading out loud might vary more. The test consisted of three fairly short texts in Icelandic that were displayed on the computer screen. An example text was first shown in order to illustrate what the actual texts would look like. A countdown preceded each text so the participants could be prepared. Reading speed was measured by the time between the text appearing on the screen and the participant pressing a button to indicate that he or she had finished reading the entire text. Participants were instructed to start reading immediately when each text appeared on the screen, and to press a response key as soon as they had finished reading the text.

IS-FORM reading test*.* The IS-FORM reading test (Sigurdardottir et. al., 2015) consists of two lists, one with 128 common Icelandic word forms and the other with 128 uncommon Icelandic word forms. Dyslexic and typical readers’ performance on the IS-FORM has been shown to differ markedly (Sigurdardottir et al., 2015). The participants were informed that their reading would be recorded with a microphone. They were instructed to read as fast as they possibly could while making as few errors as possible. One list at a time was placed in front of the participants. Number of words read per minute and percentage of correctly read words forms are the measures of interest.

IS-PSEUDO. The IS-PSEUDO reading test was developed to capture an even wider variety of reading abilities (Sigurdardottir et. al., unpublished manuscript). IS-PSEUDO consists of phonologically valid pseudoword forms; the reading of pseudowords is considered a good indicator of dyslexia (Rack, Snowling, & Olson, 1992). The number of pseudoword forms (128) and the number of syllables (343) were equal to the number of word forms and syllables on either IS-FORM list. Participants were informed before reading that the list consisted of pseudowords. They were instructed to read as fast as they possibly could while keeping errors to a minimum.

Data analysis

During the course of data collection, 3 trials of YUFOs were discovered to be defective, since the match and non-match were indistinguishable. Those trials were therefore discarded prior to further data analysis. Accuracy levels were then calculated from the remaining data (all responses except the aforementioned faulty YUFO trials). When calculating response time averages, trials with response times deviating more than three standard deviations from each individual's mean for each subtest (faces, YUFOs, scrambled, face/no face) were excluded.

One dyslexic participant performed markedly worse than other participants; his percent correct on the FYS-test, collapsed across the three discrimination tasks, was 3.32 standard deviations below the mean of the sample (dyslexic and typical readers). This dyslexic participant and his matched control were excluded from further data analysis.

All statistical tests performed were two-sided with an alpha level of 0.05. Effect sizes were estimated using Cohen's *d* (mean difference / standard deviation of difference), Pearson's *r* and the coefficient of determination R^2.

Results

Reading Abilities.

ARHQ-Ice. Dyslexic readers had significantly higher scores than typical readers on the ARHQ-Ice (paired samples t-test, $t(31) = 10.638$, $p < 0.001$, $d_z = 2.898$; table 1). Furthermore, every dyslexic participant, except for two, scored higher than their matched typical reader on the ARHQ-Ice.

ARHQ-Ice scores were significantly negatively correlated with the average of the measures of out loud reading speed (average of IS-FORM common word forms, IS-FORM uncommon word forms, and IS-PSEUDO; $r(62) = -0.711$, $p < 0.001$). Furthermore, ARHQ-

Ice scores were also significantly negatively correlated with the average of the three measures of out loud reading accuracy (*r(62)* = -0.643, *p* <0.001).

IS-FORM and IS-PSEUDO. Dyslexic readers performed considerably worse on the IS-FORM and IS-PSEUDO reading tests than typical readers (table 1). Dyslexic readers read significantly fewer common word forms (paired samples t-test, *t(31)* = 5.892, *p* <0.001, d_z = 1.917), uncommon word forms (paired samples t-test, *t(31)* = 5.838, *p* <0.001, d_z = 1.605), and pseudoword forms (paired samples t-test, *t(31)* = 4.848, *p* <0.001, d_z = 1.345) per minute than typical readers. Moreover, dyslexic readers read proportionally fewer word/pseudoword forms accurately on all word lists than controls (paired samples t-tests; common word forms: *t(31)* = 4.791, *p* <0.001, d_z = 1.223; uncommon word forms: *t(31)* = 5.916, *p* <0.001, d_z = 1.354; pseudoword forms: *t(31)* = 5.343, *p* <0.001, d_z = 1.339).

Reading in silence. Dyslexic readers read markedly fewer words per minute in silence (paired samples t-test, *t(31)* =3.925, *p* < 0.001, d_z = 0.442), suggesting that a measure of silent reading speed can be used to discriminate between dyslexic and typical readers. Correlations between the three texts were calculated to assess the reliability of the measure. Pearson's correlation coefficients were all both high and significant (r_{12}(62)=0.948, *p*<0.001, r_{13}(62)= 0.932, *p*<0.001, r_{23}(62)=0.968, *p*<0.001).

Words read per minute in silence (on all three texts) were significantly correlated with mean words read per minute out loud (average of IS-FORM common, uncommon and IS-PSEUDO; *r(62)*=0.691, *p*<0.001). Thus the convergent validity is good. In addition, the correlation between words read per minute in silence and ARHQ was negative and significant (*r(62)*= -0.585, p<0.001), further supporting the validity of the measure. The correlation between words per minute in silence (on all three texts) was also significantly correlated with mean percent of correct word forms read out loud (IS-FORM common, uncommon and ISFORM-PSEUDO; *r(62)* =0.379, *p*=0.002), suggesting that reading speed in silence could possibly be an indicator of accuracy.

Table 1. Descriptive statistics for the reading measures for dyslexic and typical readers. Significant differences (paired samples t-tests) between dyslexic and typical readers are marked with an asterisk (*).

	Dyslexic Readers		Typical Readers	
	Mean	(S.D.)	Mean	(S.D.)
*ARHQ-Ice	0.68	(0.12)	0.35	(0.11)
* IS-FORM Common				
Words/minute	75.90	(19.235)	104.50	(17.17)
*Word accuracy (%)	90.50	(5.92)	96.22	0.30
* IS-FORM Uncommon				
Words/minute	47.80	(12.77)	69.62	(12.767)
* Word accuracy (%)	76.37	(11.91)	89.11	(5.926)
* IS-PSEUDO				
Pseudowords/minute	34.98	(12.28)	50.34	(10.49)
*Pseudoword accuracy (%)	63.77	(17.27)	81.81	(8.06)
Reading speed in silence				
*Words/minute	163.32	(71.41)	267.41	(121.67)

Predicting group membership from the reading measures. In order to be assigned to the experimental group, participants were required to report having received a previous diagnosis of dyslexia. In addition, all control participants were asked before testing whether they had any history of reading difficulties, and none of them claimed that they did. We nonetheless assessed to what extent the reading measures differentiated between the two participant groups. A binary logistic regression was used with three reading measures as predictor variables (ARHQ-Ice scores, words read per minute on IS-FORM/IS-PSEUDO, and accuracy on IS-FORM/IS-PSEUDO). The model correctly predicted group membership, whether participants were dyslexic or not, in 92.2% instances $\chi^2(3) = 62.876$, $p<0.001$)

Based on the binary logistic analysis, five participants in total were wrongly classified, thereof three dyslexic participants (classified as typical readers) and two non-dyslexic (classified as dyslexic readers). However, further analysis revealed that none of these participants deviated markedly from the scores of their assigned group on all three reading measures (see figure 2). Most of them were wrongly classified based on only one variable. An examination of the z-scores on all reading measures showed that only one participant was more than three standard deviations from the mean of their assigned group on any of the tests, and that was on only one of the reading measures (a dyslexic participant that scored -3.164 standard deviations below the mean of ARHQ-Ice scores). We therefore included all of these participants in the analysis of results but note that this is a conservative decision; by removing these participants from the data, the results would remain similar and the significant observed group differences on the face task (see FYS-test section) would slightly increase (greater effect size, lower p-value).

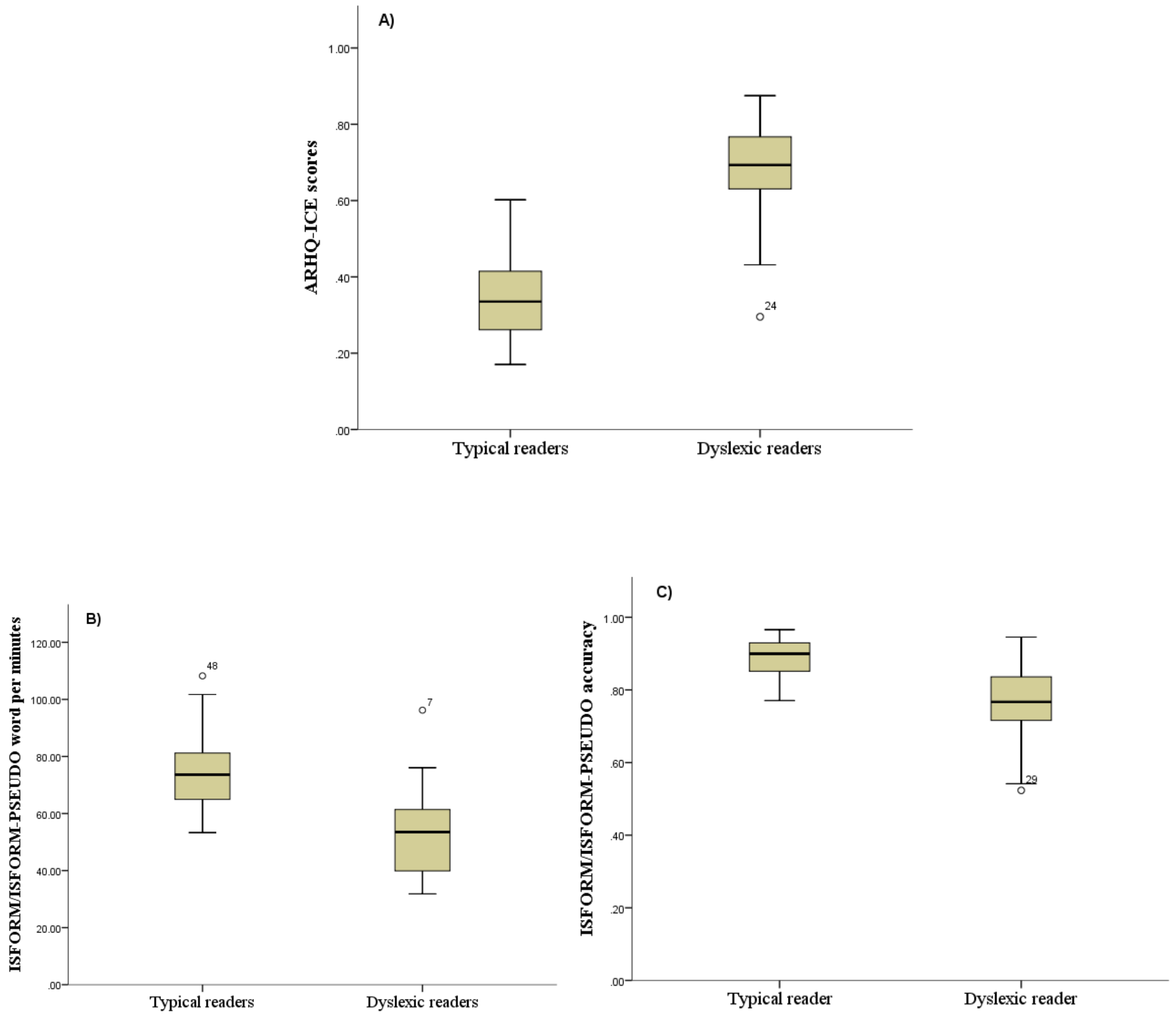

Figure 2. Reading measures for typical and dyslexic readers: ARHQ-Ice scores (A), mean IS-FORM/IS-PSEUDO accuracy (B) and IS-FORM/IS-PSEUDO mean (pseudo)word forms per minute (on ISFORM common, ISFORM uncommon and ISFORM-PSEUDO; C). The boxplot divides the data into quartiles. The box consists of the inter-quartile range (IQR) which spans from the first quartile (Q1) to the third quartile (Q3). Data points that fall 1.5 IQR below the first quartile or 1.5 IQR fall outside the whiskers and are called outliers. The

data points of the four outliers are plotted as circles. Note that although participant number 48 is an outlier on the ISFORM/IS-PSEUDO word per minutes measure (A), he is not one of the five wrongly classified participants, since he is a member of the control group that reads unusually fast.

FYS-test. No significant group differences in response times were found on any FYS-tasks (table 2): face task ($t(31)=1.281$, $p=0.21$, $d_z=0.283$), YUFO task ($t(31)=0.703$, $p=0.487$, $d_z=0.153$), scrambled task ($t(31)= 0.007$, $p=0.994$, $d_z= 0.002$).

A moderate to strong positive correlation was found between accuracy on all the FYS tasks; the face and YUFO task ($r(62)=0.665$, $p<0.001$), the face and the scrambled face task ($r(62)=0.540$, $p<0.001$) and the YUFO and the scrambled face task ($r(62)=0.537$, $p<0.001$). That indicates some common factors of the tasks.

The faces were correctly discriminated on a high percentage of trials in both groups although dyslexic readers performed worse (dyslexics: M=85%, typical readers: M=89%; chance level: 50.0%; table 2; figure 3). Paired sampled t-tests revealed that this difference was significant ($t(31)= 2.256$, $p=0.031$, $d_z= 0.536$). The accuracy of dyslexic and typical readers did not significantly differ for either the YUFO task, ($t(31)= 0.125$, $p=0.901$, $d_z= 0.033$), or the scrambled face task, ($t(31)=1.619$, $p=0.116$, $d_z= 0.368$).

Table 2. Descriptive statistics for dyslexic and typical readers. Significant differences (paired samples t-tests) between dyslexic and typical readers are marked with an asterisk (*).

	Dyslexic Readers		Typical Readers	
	Mean	(S.D.)	Mean	(S.D.)
FYS Tests				
Accuracy (%)				
*Faces	85.05	(7.524)	88.76	(6.303)
YUFOs	85.91	(8.535)	86.18	(7.847)
Scrambled	72.88	(13.94)	77.35	(10.039)
Response times (ms)				
Faces	2693	(1118)	2420	(785)
YUFOs	2932	(1420)	2736	(1124)
Scrambled	3514	(1510)	3517	(1448)

Face/no face				
Accuracy (%)	85.05	(7.73)	86.96	(24.4)
Response times (ms)	868	(244)	843	(202)
Behavioral Assessment				
*Childhood ADHD symptoms	27.75	(13.11)	14.19	(8.43)
*Current ADHD symptoms	20.59	(10.704)	10.47	(4.88)

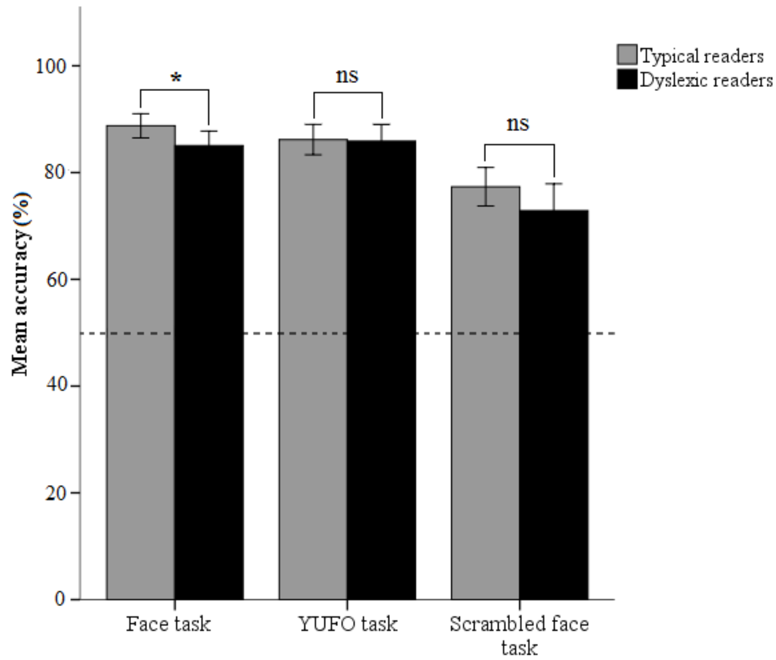

Figure 3. Mean accuracy on the FYS-test for typical and dyslexic readers in percentage of correct trials. Expected chance performance is 50% (dashed line). Error bars mark the 95% confidence interval of the mean accuracy. Significant differences (paired samples t-tests) between dyslexic and typical readers are marked with an asterisk (*), and non-significant differences are marked with “ns”.

Paired sample t-tests were performed excluding the five participants and their matches that were wrongly classified as dyslexic/non-dyslexic according to a binary logistic regression. Results were similar; dyslexic and typical readers differed significantly in accuracy on the face task ($t(26)=3.453$, $p=0.002$, $d_z= 0.778$) but not on either the YUFO ($t(26)=0.633$, $p=0.532$, $d_z= 0.177$) or scrambled task ($t(26)=1.737$, $p=0.094$, $d_z= 0.437$).

Regression analyses were performed to assess whether accuracy on the three tasks of the FYS-test predict reading ability. The independent variables were accuracy on each FYS-tasks (three regressors: the face task, the YUFO task and the scrambled face task) and the dependent variables were the three reading measures (ARHQ-Ice scores, IS-FORM/IS-PSEUDO mean words per minute and IS-FORM/IS-PSEUDO mean accuracy). Thus three separate regression analyses were performed, one for each reading measure.

Accuracy on the face task, YUFO task and the scrambled face task significantly predicted ARHQ-Ice scores ($F(3, 63)=3.016$, $p=0.037$, $R^2= 0.15$) and IS-FORM/IS-PSEUDO accuracy ($F(3, 63)=3.939$, $p=0.012$, $R^2= 0.21$). In contrast, accuracy on the three task of the FYS-test did not predict mean words read per minute on IS-FORM/IS-PSEUDO ($F(3, 63)=0.791$, $p=0.504$, $R^2= 0.087$). Furthermore, conditional coefficients of each task were assessed. Accuracy on the face task significantly predicted the mean IS-FORM/IS-PSEUDO accuracy ($\beta= 0.565$, $t(63)= 3.096$, $p=0.003$) and scores on ARHQ ($\beta= -0.441$, $t(63)=2.433$, $p=0.018$), when performance on the scrambled and YUFO tasks was kept fixed. No other conditional coefficients were significant (all t values <1.267, all significance values $p<0.210$).

ADHD. Ten dyslexic participants and two typical readers reported a previous ADHD diagnosis. Dyslexic participants also had considerably higher scores than typical readers on the ADHD screening test for both childhood (paired samples t-test, $t(31)= 4.412$, $p = 0.001$, $d_z =1.230$) and current (paired samples t-test, $t(31) = 5.341$, $p<0.001$, $d_z = 1.216$) symptoms of ADHD (table 2). Even the dyslexic readers who reported no prior ADHD diagnoses reported greater symptoms of ADHD than their matched typical readers, on both adult (paired samples t-test, $t(21) = 3.450$, $p = 0.002$, $d_z = 0.962$) and childhood symptoms (paired samples t-test, $t(21) = 2.326$, $p = 0.03$, $d_z = 0.760$; 22 pairs included, 10 pairs excluded).

Accuracy on the face task of the FYS-test was regressed onto dyslexic diagnosis (coded dyslexia=1, non-dyslexic=0), ADHD diagnosis (coded ADHD=1 and no diagnosis=0) and current and childhood ADHD symptoms. The regression analysis showed that dyslexia predicts performance on the face task of the FYS-test when controlling for ADHD diagnosis and current and childhood ADHD symptoms ($\beta= -0.058$, $t(63)= 2.427$, $p=0.018$). Therefore, the difference between dyslexics and typical readers face discrimination ability cannot be attributed to attentional deficits.

Face/No face test. For unknown reasons, data was not recorded for one participant. He and his match were therefore excluded from data analysis of this test. No differences were found between dyslexic and typical readers on this face detection test. The difference between accuracy of the typical readers and the dyslexic readers was non-significant ($t(30)= 0.466$, $p=0.645$, $d_z= 0.133$), and the difference between the response times as well ($t(30)=0.594$, $p=0.557$, $d_z= 0.124$) (table 2).

Discussion

The study had three main goals; first, to firmly establish the impaired face processing of dyslexic readers in a large sample; secondly, to pinpoint the specificity of the perceptual impairment, including determining to which extent it is specific to higher level visual processing; lastly, we wanted to assess whether the proposed higher level visual processing deficits of dyslexic readers extend to the perception of novel objects. Each point will be discussed in detail, followed by a general discussion of the results.

Face processing impairments

The first goal of the study was achieved; the dyslexic readers were less accurate on the face discrimination task of the FYS-test than the typical readers. These results are in line with converging evidence of the concurrence of dyslexia and face processing deficits (Gabay et al. unpublished manuscript; Sigurdardottir et al., 2015; Tarkiainen et al., 2003) and reports of the underactivity of the right FFA (Monzalvo et al. 2012) and VWFA (Richlan et al. 2011) in dyslexic readers. In addition, accuracy on the face discrimination task predicted accuracy on the IS-FORM/IS-PSEUDO reading test, when statistically controlling for accuracy on the YUFO and scrambled face task, indicating that those who have poor face processing abilities seem to have poor word processing as well. Those results are consistent with evidence of the interdependency of word and face processing (Behrmann & Plaut, 2013; Dehaene et al., 2011; Starrfelt et al., 2016)

An important distinction must be made when considering the results of the current study in relations to Sigurdardottir et al. (2015). The task used in Sigurdardottir et al. (2015) required participants to memorize and recognize faces. Working memory deficits have long been implicated with dyslexia, although most of these studies have revolved around verbal memory (de Jong, 1998; Gathercole, Alloway, Willis & Adams, 2006). Since the face task of the FYS-test revolves around discriminating simultaneously presented faces and thus has minimal working memory and long-term memory requirements, memory deficits are unlikely to be a sole determining factor in the facial perception deficits of dyslexia seen in the current study.

In Sigurdardottir et al. (2015) dyslexic readers performed worse than typical readers on a face recognition task, but no significant differences in holistic face processing were found, leading the authors to suggest that these problems arise from the faulty part-based processing of faces. Likewise, Gabay et al. (unpublished manuscript) found no differences between dyslexic and typical readers' performance on the face inversion effect, a common measure of holistic processing. Participants of the current study could rely on part-based processing as well as configural or holistic processing on the face discrimination task. Therefore, it remains an open question whether dyslexic readers performed worse on the face perception task of the FYS-test as a result of deficits specific to part based processing, or just face processing in general. The left fusiform gyrus, which is particularly involved in part-based processing (Bourne et al., 2009; Rossion et al., 2000), is hypoactive in dyslexic readers (Richlan et al., 2011). Therefore, the role of part-based processing deficits in the face processing impairments of dyslexia warrants further research. Even though previous findings have not revealed differences in holistic face processing of dyslexic and typical readers (Gabay et al., 2015; Sigurdardottir et al., 2015), it is plausible that dyslexic readers might show some deficits. Those speculations are based on the notion that holistic processing is the hallmark of face perception and hypoactivity has been reported in the right FFA in Monzalvo et al. (2012), an area crucial to holistic face processing (Rossion et al. 2000, Bourne et al., 2009).

The specificity of the visual impairment

Scrambled face task. The second goal of the study was to determine if the visual impairment in dyslexia is specific to higher level visual processing. In order to be able to conclude that face perceptual deficits of dyslexic readers do not simply result from a general impairment of the visual system, a control task (the scrambled face task) was required. Scrambled faces share low level visual properties with non-scrambled faces, yet the group of typical readers and the dyslexic group did not significantly differ in either accuracy or response times for scrambled faces, supporting that dyslexia is associated with higher level rather than lower level visual processing deficits. Similarly, Ben-Yehudah and Ahissar (2004) found no differences between dyslexic readers and controls on a low level simultaneous discrimination task of spatial frequencies. Importantly, the link between the deficits in the face and word processing of dyslexic individuals is not fully explained by general impairments in visual discrimination. When accuracy on the scrambled and YUFO tasks was controlled for, accuracy on the face discrimination task still predicted reading accuracy and history of reading difficulties (ARHQ-Ice scores).

It is worth noting that even though low level visual regions such as the primary visual cortex could hypothetically be sufficient to discriminate between tilted scrambled faces (since they only contained basic information of brightness and contrast which is preferred by the cells of V1; Hubel & Wiesel, 1962; Mesulam, 1998) it is very likely that the task required some visual or attentional processing outside the primary visual cortex. At the end of the experiment, participants were asked which strategies they used on each task of the FYS-test. Some participants reported searching for figures or shapes in the scrambled images to solve the scrambled face task. In those cases, they might have been using some higher level visual processes. Since the cells of the primary visual cortex have very small receptive fields (Mesulam, 1998), it can also be presumed that some higher level processing was needed to compare scrambled images across different locations. The dorsal stream is involved in orientation processing (Valyear et al., 2006), and therefore it is likely that participants had to rely on the dorsal stream in order to solve this task. Nevertheless, it is unlikely that object selective regions are heavily involved, since by definition, they are more responsive to objects than to scrambled stimuli (Grill-Spector, 2009).

In a face perception task in Gabay et al. (unpublished manuscript), where the perceptual complexity was manipulated, differences in accuracy of dyslexic and typical readers emerged only in the perceptually demanding conditions. Those findings might suggest that that dyslexic readers tend to perform poorly on demanding tasks, but similar to typical readers in easier conditions (Gabay et al. unpublished manuscript). Furthermore, dyslexic readers showed greater cost in response times than controls on a simultaneous face discrimination task when the task required matching the target and the choice face over orientation (Gabay et al. unpublished manuscript). The authors suggested the results provided evidence of abnormal face processing of dyslexic readers. However, Gabay et al. did not include a non-face control task as in the current study. Thus, it is impossible to rule out that the observed difference between the performance of the dyslexic and typical readers on the face discrimination task was not simply a consequence of task difficulty or general visual impairments of the dyslexic readers. In the current study, both dyslexic participants and controls tended to perform worst on the scrambled face task out of all the FYS-tasks, yet no consistent group differences were found on this most demanding task. Therefore, the results of the current study cannot be explained by non-specific effects of task difficulty.

YUFOs: Perception of novel objects. To establish whether the deficit of higher level visual processing of dyslexic readers extends to the processing of novel objects, the YUFO task was implemented in the FYS-test. Although both the face task and the YUFO task required higher level visual processing and within category discrimination, results were divergent; dyslexic participants and controls differed in accuracy on the face task but not the YUFO task. Those findings suggest two possible conclusions. The first interpretation is that the visual impairments of dyslexic readers might be specific to the processing of words and faces. Secondly, the perceptual impairments of dyslexia might be specific to higher level visual processing of objects with which people have extensive visual experience. The latter option seems more plausible, since dyslexic readers seem to be not only impaired in face processing but also in the processing of other familiar objects (Sigurdardottir et al., 2015).

Like YUFOs, greebles and ziggerins are novel computer generated objects of different visually similar categories (Gauthier et al., 1998; 1999; 2000; Wong et al., 2009). Increased experience with those objects has an impact on how they are processed: with growing experience the visual processing of those objects becomes more holistic (Gauthier, et al., 1998; Wong et al., 2009). Furthermore, the FFA responds more to such objects after people have been trained to individuate them, demonstrating the plasticity of the visual system (Gauthier, et al., 1998). Since dyslexic readers show impaired face processing and hypoactivity in the fusiform gyrus, the area that responds more to training, it is unclear whether they are able to benefit as much as typical readers from visual experience. Therefore, it would be interesting to assess whether differences between the discrimination ability of dyslexic and typical readers would emerge on the YUFO task following YUFO individuation training. Brachacki et al. (1995) showed that dyslexic readers' traffic sign recognition ability seemed to hardly benefit from driving experience, contrary to typical readers whose traffic sign recognition improved with driving experience (Brachacki et al., 1995). Thus, dyslexic readers might lack the ability to utilize visual experience for the pruning of neural processing in object selective regions in the ventral stream.

Further discussion of the FYS-test

The differences between groups of the current study were limited to accuracy on the face task, but the response times of dyslexic and typical readers did not markedly differ on any of the FYS tasks. The results of the current study interesting in the light of the notion that slow responding has often been linked to dyslexia. Our results might possibly indicate that dyslexic readers are not necessarily slower at processing visual information but have a difficulty in analysing the high grain details needed to distinguish between expertise objects such as two very similar faces and words.

Performance on the three discrimination tasks (faces, YUFOs and scrambled faces) was moderately to highly correlated. In contrast, Gauthier et al. (2014) found a weak correlation between recognition of faces and objects of non-expertise. Note that since they used recognition tasks, performance was partly influenced by a shared memory factor, whereas here presentation was simultaneous. Therefore, the effect of memory was minimized, but general perceptual ability played a bigger role. We suggest that the high correlation in the current study can be partly explained by factors that affect performance irrelevant of the type of task, such as general perceptual ability and motivation. Moreover, the higher than expected correlation between faces and YUFOs could be related to the fact that the faces of the FYS task were generated without texture cues. Face recognition relies heavily on high spatial frequency cues such as texture cues (Costen, Parker & Craw, 1994; Fiorentini, Maffei, & Sandini, 2013) while the ability to perceive other objects seems to depend more on basic perception of edges and lines (Biederman & Kalocsai, 1997). Hence, part of the unique variance of face perception might be assigned to high spatial frequency processing. By removing some of the characteristics of face processing that distinguishes it from the perception of other objects, face recognition tasks might inevitably become more correlated with the perception of objects.

Another possible consequence of using faces mostly devoid of texture cues is that it might have attenuated the observed face processing deficits of the dyslexic readers. The area that is hypoactive in dyslexics is positioned in the left hemisphere, which is involved in processing of high spatial frequency information, such as letters (Peyrin, Chauvin, Chokron & Marendaz, 2003). The right FFA mainly processes facial shape information, but the left FFA processes information of both facial shape and facial surface properties/texture cues (Jiang, Dricot, Blanz, Goebel & Rossion, 2009). Thus, the difference between dyslexic and typical readers might have been even larger if participants would have had to rely on texture cues rather than rough shape cues.

Attention

Dyslexia is highly comorbid with ADHD (Germanó, Gagliano & Curatolo, 2010). Difficulties with visual attentional span have been named as a factor in dyslexia (Bosse. Tainturier & Valdois., 2007; Valdois et al., 2004). In the sample of this current study ADHD was more common in the dyslexic group than the non-dyslexic. In addition, even dyslexic individuals who had not been diagnosed with ADHD showed more current and childhood symptoms of ADHD than control participants. Given the role of attention in dyslexia and the prevalence of the disorder amongst dyslexic readers, it can be presumed that ADHD might greatly impact dyslexic readers' performance on perceptual tasks. Dyslexia however predicted performance on the face discrimination task of the FYS-test even when ADHD diagnosis and symptoms were statistically controlled. Those results suggest that dyslexic individuals' impaired face perceptual abilities cannot solely be attributed to attentional deficits as assessed by ADHD diagnosis or symptoms.

Education levels

Participants' levels of education were matched within pairs, to ensure that differences in perceptual performance could not be attributed to differences in education. Education might have an effect since literacy drives the hemispheric lateralization of face processing and increases flexibility in the use of strategies in face perception (holistic or part-based processing; Ventura et al., 2013).

It is worth mentioning that the sample of the current study was not entirely reflective of the Icelandic population given the large number of participants that had only finished the first level of education. The education level in the Icelandic is rather high. 36% of the nation have a university education, 75% (age 26-64; OECD Better Life Index, n.d.) have completed upper secondary education, and only 27.8% of the nation has completed elementary school or less (Hagstofa Íslands, 2013). However, it is unlikely that this issue had crucial impact on the current results. If anything, the high proportion of individuals with a low level of education in the sample might have reduced the difference between dyslexic and typical readers' accuracy on the face discrimination test given that low education level is an indicator of insufficient reading experience, which again limits flexibility in face perception strategies.

Results in context of the phonological view

It is important to note that the result of the current study do not necessarily contradict the phonological view. The phonological problems of dyslexic individuals are well supported (Pennington et al., 1990; Ramus et al., 2003; Veluttino et al., 2004) but the results of the current study suggest that the phonological deficits are just one aspect of a more extensive disorder, that ranges from impairments of language to deficit of visual perception. The two aspects could be connected partly through abnormal activity of the VWFA and surrounding areas in dyslexic readers, a proposed main cause of their face perception impairments (Gabay et al., unpublished manuscript; Sigurdardottir et al., 2105). The phonological impairments of dyslexic children are correlated with reduced functional connectivity between the VWFA and reading-related brain regions (such as inferior frontal and inferior parietal brain regions), but functional connectivity is not related to phonological disruptions of non-dyslexic children (van der Mark et al., 2011).

Fundamentally, dyslexia is a complication with reading and writing, independent of intelligence or education (Blau et al., 2010; Ahissar, 2007; Serrano & Defior, 2008). Reading demands an interaction of many cognitive processes: to concentrate or focus on a text, perceive letters and words, and decode those words to relevant sounds and meaning. It is possible that any step of the process can go wrong and therefore dyslexia might have a variety of causes.

Conclusion

Our results clearly establish that dyslexia involves abnormal visual processing and is thus not merely a disorder of language processing. In line with converging evidence of the dependency of word and face processing, dyslexic readers have poorer face perception abilities than typical readers. They perform comparably to typical readers on a scrambled face test, indicating that the perceptual deficits are not general but are limited to higher level visual processing. Dyslexic readers did not markedly differ from controls on a novel object discrimination task, highlighting the importance of perceptual experience in the manifestation of visual processing deficits in dyslexia.

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