Cognition 175 (2018) 157–168

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

Specific problems in visual cognition of dyslexic readers: Face discrimination deficits predict dyslexia over and above discrimination of scrambled faces and novel objects

Heida Maria Sigurdardottir*, Liv Elisabet Fridriksdottir[1], Sigridur Gudjonsdottir[1], Árni Kristjánsson

Department of Psychology, University of Iceland

ARTICLE INFO

Keywords:
Dyslexia
Reading
Face perception
Object perception
Visual expertise

ABSTRACT

Evidence of interdependencies of face and word processing mechanisms suggest possible links between reading problems and abnormal face processing. In two experiments we assessed such high-level visual deficits in people with a history of reading problems. Experiment 1 showed that people who were worse at face matching had greater reading problems. In experiment 2, matched dyslexic and typical readers were tested, and difficulties with face matching were consistently found to predict dyslexia over and above both novel-object matching as well as matching noise patterns that shared low-level visual properties with faces. Furthermore, ADHD measures could not account for face matching problems. We speculate that reading difficulties in dyslexia are partially caused by specific deficits in high-level visual processing, in particular for visual object categories such as faces and words with which people have extensive experience.

1. Introduction

Despite the high prevalence rate (5–17.5%) of developmental dyslexia (Shaywitz, 1998) and decades of research, its underlying cognitive and biological causes are still debated. Dyslexia is typically thought to be a language disorder, and there is good evidence for phonological deficits in dyslexia (Catts, 1989; Díaz, Hintz, Kiebel, & von Kriegstein, 2012; Pennington, Orden, Smith, Green, & Haith, 1990; Ramus et al., 2003; Shaywitz & Shaywitz, 2005; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Yet the role of phonological factors in reading varies across languages of different orthographic depth (Ziegler et al., 2010), and some dyslexic readers can perform well on phonological tests but do not read fluently (Valdois, Bosse, & Tainturier, 2004). Dyslexia is likely a multifaceted disorder, and phonological factors as well as other factors could contribute to reading problems.

1.1. Dyslexia and face perception

Recently, evidence of interdependencies of face and word processing mechanisms has sparked interest in a potential link between dyslexia and abnormal face processing (e.g. Behrmann & Plaut, 2012; Dehaene & Cohen, 2011; Dundas, Plaut, & Behrmann, 2013; but see Robotham & Starrfelt, 2017; Starrfelt, Klargaard, Petersen, & Gerlach, 2016). Of particular relevance are studies showing that (a) people who acquired what initially appeared to be specific reading problems after brain damage also had subtle problems with face perception, and (b) high-level ventral stream regions in or near the left fusiform gyrus that support word and face recognition are hypoactive in dyslexic readers (for an extended discussion of the theoretical underpinnings, see Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015).

In Sigurdardottir et al. (2015), we reported that dyslexic readers were worse than matched typical readers at recognizing faces and other familiar objects at the individual level (within-category or subordinate-level recognition), consistent with the possibility that reading problems in developmental dyslexia might be a salient manifestation of a more general high-level visual deficit. High-level visual cognition, thought to be dependent on brain regions such as the fusiform gyrus in the ventral visual stream, involves visual processing dedicated not to the analysis of local image structure but to the structure of the external world, especially object perception and recognition (Cox, 2014; DiCarlo & Cox, 2007). Problems with high-level visual cognition therefore do not indicate that people have trouble seeing – they have problems with making sense of what they see. Nevertheless, there is no consensus in the literature on links between developmental dyslexia and high-level

* Corresponding author at: Aragata 14, 101 Reykjavik, Iceland.
E-mail address: heidasi@hi.is (H.M. Sigurdardottir).
[1] These authors contributed equally and are listed in alphabetical order.

https://doi.org/10.1016/j.cognition.2018.02.017
Received 7 July 2017; Received in revised form 13 February 2018; Accepted 14 February 2018
Available online 16 March 2018
0010-0277/

visual cognition in general or face perception in particular.

Rüsseler, Johannes, and Münte (2003) reported no significant differences between the ability of participants with and without dyslexia in judging whether particular faces had been presented before or not. There was, however, a numerical difference with a non-trivial effect-size so the study may have been underpowered. Additionally, as the same images were used in the learning and study phase, participants may have relied on low-level visual cues to recognize the faces. Holmes and McKeever (1979) reached a similar conclusion, but again, low-level cues were not adequately controlled for (see also Liberman, Mann, Shankweiler, & Werfelman, 1982).

Korinth, Sommer, and Breznitz (2012) found no differences in the ability of slow and fast reading university students to quickly decide whether photographs showed men or women. Performance was close to ceiling so possible differences in facial recognition abilities might not have been detectable. It is uncertain whether this task measures face recognition abilities, as gender identification can survive impairments in face recognition (Tranel, Damasio, & Damasio, 1988). It is also unclear whether participants could rely on non-facial gender cues such as hairstyle or hair length.

Smith-Spark and Moore (2009) found no differences in the ability of dyslexic and non-dyslexic university students to name celebrity faces. Non-dyslexic participants were, however, faster at naming famous faces that were learned early rather than late in life (age of acquisition effect), which was less apparent for dyslexic participants suggesting that experience with faces differentially affects people with and without dyslexia.

Brachacki, Fawcett, and Nicolson (1994) tested the face and voice recognition of seven dyslexic and eight non-dyslexic adults. While face recognition was at ceiling, dyslexic readers did worse than typical readers on a recognition test given a week later. The difference, while non-trivial, was not significant, which could reflect the small sample.

Aaron (1978) subdivided a sample of dyslexic children into dysphonetics (analytic-sequential deficient) and dyseidetics (holistic-simultaneous deficient) based on the nature of their spelling errors. All children were shown photographs of faces that had no readily distinguishable features such as a moustache, hair style, or dress. The dyseidetic children correctly identified significantly fewer photographs than the dysphonetic children whose performance was similar to a control group.

Tarkiainen, Helenius, and Salmelin (2003) tested eight adults with dyslexia and ten without dyslexia on a short version of the Benton facial recognition test (Benton, Sivan, Hamsher, Varney, & Spreen, 1978), and a computerized face recognition test where people saw a target face in the upper half of the screen and judged which of two choice faces in the lower half matched the upper face by quickly pressing a button. Dyslexic participants made more errors than controls on the Benton test and were slower at matching to facial identity in the computerized test.

Pontius (1976,1983) reported that dyslexic children were more likely than controls to draw so-called neolithic faces where spatial relations in the upper part of the human face are misrepresented, suggesting unusual or distorted facial representations. Pontius suggested that such configurations are analogous to the visual experience of people with prosopagnosia. Finally, Gabay, Dundas, Plaut, and Behrmann (2017) tested the face perception abilities of 12 matched pairs of dyslexic and non-dyslexic university students finding that the dyslexic group had atypical and comparatively deficient visual processing of faces.

In sum, there are reports of both intact as well as deficient face processing abilities of people with dyslexia. However, some studies were small-scale and lacked statistical power, did not control for low-level visual cues or other cues not related to face individuation, or suffered from problems that makes their interpretation difficult. Whether developmental dyslexia involves face processing problems is therefore still unclear.

1.2. The specificity of problems in face perception

If dyslexic readers do indeed have problems with face processing, the specificity of such deficits is also unknown. Face recognition deficits could reflect non-specific factors such as general problems with memory or attention, both of which have been reported in people with dyslexia (e.g. de Jong, 1998; Gathercole, Alloway, Willis, & Adams, 2006; Germano, Gagliano, & Curatolo, 2010). If the problems were visual, a visual deficit in dyslexia could be low-level (e.g. magnocellular; Skottun, 2000; Stein & Walsh, 1997) or more high-level (e.g. a problem with processing shape cues). A low-level deficit in the processing of fundamental characteristics of faces and words, such as their orientation and spatial frequency contents, could appear as a problem with recognizing visual faces and words.

If visual problems in dyslexic readers are high-level, they could be specific to particular object categories (specific mechanisms), such as faces, words, and other real-world objects that people have experience with, or they could generalize to all visual object classes, even novel ones (general mechanisms). While faces and words are perhaps the two categories that people in general have the most experience with, as people have to be able to tell apart thousands of similar-looking faces and words, they also have some experience with individuating other real-word objects. Our recent work indicates that dyslexic readers have problems with recognizing words, faces, and other real-world objects at the individual level (Sigurdardottir et al., 2015) and that they might not learn from their visual experience to the same extent as typical readers (Sigurdardottir et al., 2017). If visual experience does not successfully reshape the visual system of dyslexic readers to become selective for category-specific features important for individuating familiar object classes, then discriminating and recognizing objects of those categories would be impaired.

As Richler, Wilmer, and Gauthier (2017) point out, measuring performance for novel objects might be a preferable way of probing category-general object recognition mechanisms because performance is not "contaminated" by individual differences in category-specific experience, or – we add – potential individual differences in experiential effects on high-level visual mechanisms. Visual recognition abilities for novel objects are indeed dissociable from visual recognition abilities for familiar object classes, in line with these being supported by at least partially separable mechanisms (Richler et al., 2017).

Our previous work indicates that visual recognition problems in developmental dyslexia are not completely generic, as there were no significant differences between people with and without dyslexia on a challenging color recognition test (Sigurdardottir et al., 2015). Gabay et al. (2017) also found no consistent problems in people with dyslexia for individuating cars, although they noted that the dyslexic readers were relatively slow at responding to all categories. Our prior work (Sigurdardottir et al., 2015) indicates however that face recognition problems in dyslexia generalize to difficulties with subordinate-level recognition of at least some familiar non-face object classes (individuation of birds, butterflies, cars, houses, or planes). This is fully in line with the fact that the left fusiform and inferior temporal gyri are hypoactive in adult dyslexic readers (Richlan, Kronbichler, & Wimmer, 2011) and that the left fusiform gyrus is smaller in people who carry a genetic sequence variant associated with dyslexia (Ulfarsson et al., 2017). The fusiform and inferior temporal gyri support the individuation or subordinate-level categorization of faces as well as non-face objects (Gauthier, Anderson, Tarr, Skudlarski, & Gore, 1997; Haist, Lee, & Stiles, 2010), especially following experience with individuating the objects (e.g. Gauthier, Tarr, Anderson, Skudlarski, & Gore, 1999; for a recent review, see Sigurdardottir and Gauthier (2015) but see e.g. Rhodes, Byatt, Michie, and Puce (2004). Whether such discrimination problems generalize to novel objects or even non-objects that share low-level visual properties with problematic object classes is unknown.

1.3. Current aims

We conducted two experiments where a total of over 100 people with and without a history of reading problems were run on the same face discrimination task. Participants were to match faces across viewpoint, making reliance on low-level visual cues detrimental to task performance. All faces were rendered with the same texture, so that participants would have to rely on facial shape. We furthermore tested the specificity of potential face discrimination problems in a sample of matched dyslexic and typical readers.

We address the following questions: (a) Are reading problems associated with deficits in subordinate level categorization of faces during simultaneous presentation, where memory factors should play a minimal role and only fine shape differences are task relevant? (b) Are perceptual problems in dyslexia specific to real-world object classes such as faces that people have extensive experience with or do they generalize to another homogeneous object class that people have no prior experience with? (c) Are face perception problems explained by difficulties with processing low-level visual properties? (d) Can face perception problems be explained by a lack of attention or vigilance?

2. Method

The study was approved by the Icelandic National Bioethics Committee (protocol 14-027), reported to the Icelandic Data Protection Authority, and was carried out in accordance with the Declaration of Helsinki. Participants gave informed consent. Two experiments were run concurrently. Each participant in experiment 1 participated in accordance with prerecorded instructions in a setting of their choosing. Participants in experiment 2 completed the experiment under the guidance of the researchers in a well-lit, quiet room, with computerized tasks run using a CRT monitor (85 Hz, resolution 1024 × 768). Tasks in experiment 1 were a subset of the tasks run in the more controlled experiment 2. These experiments are therefore described together.

2.1. Participants

2.1.1. Experiment 1

Participants were 39 undergraduate students at the University of Iceland. Thirty were female, six were male, and three did not specify their gender. 29 people reported their age: age range was 21–44 with a mean age of 24.2. Students could receive partial course credit for participation; inclusion in the current dataset was on a voluntary basis. The sample was not randomly selected from the student body and likely overrepresented students with reading problems. The stopping rule for data collection was to include all voluntary participants within a particular time period.

2.1.2. Experiment 2

Thirty-three dyslexic readers (reporting a prior diagnosis; 21 women and 12 men) and 33 matched typical readers 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 roughly to high school, gymnasium, college, and university, respectively) participated in experiment 2 (see also Section 3.2.2). All were native Icelandic speakers, and reported normal hearing and normal or corrected vision with glasses or contacts. Participants were only included if they reported no diagnosis of an autistic spectrum disorder, as those individuals often have impaired face recognition (e.g. Boucher & Lewis, 1992; Schultz, 2005; but see Jemel, Mottron, & Dawson, 2006). The dyslexic participants ranged in age from 18 to 49 (mean 26.1) years, 18 to 52 years (mean 25.9) for typical readers. In both (matched) groups sixteen individuals had completed the first level of schooling, fourteen the second level of schooling, two the third level and one had completed the fourth level of schooling. Participants were unpaid, but entered a lottery where five randomly selected participants could receive a 10.000 kr. (approx. US$80) gift voucher. Four additional participants were not included: One dozed off during testing, another initially reported being a typical reader but turned out to have a prior diagnosis of dyslexic dysgraphia, and matched typical readers (of the same age, gender, and educational level) were not found for two dyslexic readers. The stopping rule for data collection was to reach 35 matched participant pairs or the maximum number of pairs within a particular time period, whichever came first.

2.1.3. Test material and procedure

Participants in experiment 1 completed the face matching part of the Face-YUFO-Scrambled test (FYS-test) and answered the Adult Reading History Questionnaire (ARHQ-Ice). Participants in experiment 2 answered questions regarding prior diagnoses of disorders and their history of medication, and completed the following measures: FYS-test, questionnaires of ADHD, ARHQ-Ice, Reading in silence, IS-FORM reading test, IS-PSEUDO reading test. Additionally, participants completed two measures not reported here: self-reported experience of objects, which was part of a separate pilot study, and a face detection task that was found to be unreliable. Visual stimuli were presented using PsychoPy (Peirce, 2007). Participants in experiment 2 had a choice of hearing questionnaires read aloud or to read themselves.

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

The FYS-test created for this study consisted of three discrimination tasks, each with different stimuli: computer-generated faces (F), novel computer-generated objects called YUFOs (Y; copyright Michael J. Tarr, 2006: http://wiki.cnbc.cmu.edu/Novel_Objects), and scrambled faces (S), see Fig. 1. Participants in experiment 1 completed the face matching portion (but not YUFO matching or scrambled face matching) of the FYS-test. Participants in experiment 2 completed all three tasks.

The test began with two practice trials for each discrimination task (FYS) 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. On each trial, three stimuli were presented simultaneously (e.g. three faces). The task was to match to sample. The sample was presented at screen center with two comparison stimuli on each side – one match and one non-match (positioned approximately 9 degrees of visual angle to the left and right of center in experiment 2). Participants indicated the location of the match with a left or right

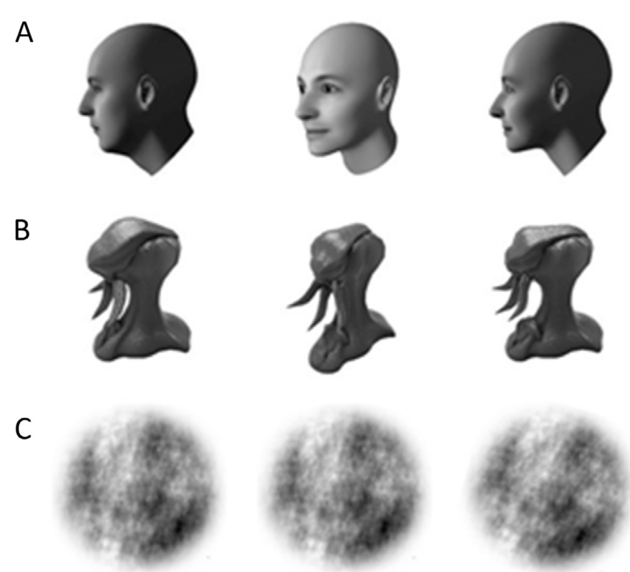

Fig. 1. Examples of stimuli used in each task of the FYS-test. (A) Faces: here the right face is the same as the sample face in the middle. (B) YUFOs: here the right novel object matches the middle sample. (C) Scrambled faces: the three images are identical except for the tilt; the left stimulus matches the middle sample.

keypress. The stimuli stayed on-screen until participants responded. The intertrial interval was 200 ms from button press.

The non-match stimuli for all trials were selected at random when creating the trials but were the same for all participants. Therefore, all participants compared the same stimuli, but in different order allowing analyses of individual trials (see Section 3.2.4.7). However, whether the match stimulus appeared to the left or the right was randomized for each participant (in experiment 1) or matched participant pair (in experiment 2, i.e. matched participants got the same randomized left/right order). Trial order was randomized for each participant (in experiment 1) or matched participant pair (in experiment 2), separately for face, YUFO, and scrambled trials. Matched participants therefore saw the same randomized order. Trials within the three tasks were further divided into four blocks presented in random order for each participant (experiment 1) or matched pair (experiment 2), with the constraint in the latter case 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 minimizing errors. Both accuracy and response times were measured.

2.1.5. FYS-test stimuli

2.1.5.1. Faces. The face stimuli were rendered images of three-dimensional human faces (created with FaceGen, Singular Inversions Inc.). Forty-eight random symmetric Caucasian faces were created (approximately 5° of visual angle in experiment 2). The texture cues of all faces were identical, so participants had to rely on shape cues only. The faces could be displayed at five different viewpoints: 0° (frontal view), ± 45° (left or right half profile view) or ± 90° (left or right full profile view). Each face appeared four times as a sample, at either the 45° or −45° viewpoint. The two comparison stimuli were always displayed from the same viewpoint, either 0° or ± 90°. Each face sample therefore appeared two times at −45° viewpoint (once with match/non-match with −90° viewpoint and once with 0° match/non-match) and twice at 45° viewpoint (match/non-match with 90° or 0° viewpoint). The viewpoint difference between sample and comparison stimuli was therefore always 45°.

2.1.5.2. Yufos. The novel objects, YUFOs (copyright Michael J. Tarr, 2006), were downloaded from the CNBC wiki website (http://wiki.cnbc.cmu.edu/Novel_Objects). Background was removed. YUFOs are visually similar three-dimensional objects of different categories or families, consisting of individuals of two “genders”. Objects within each family have the same basic structure. Subtle characteristics distinguish each individual YUFO, such as differences in “head” and “body” shape (Gauthier, James, Curby, & Tarr, 2003). In the FYS-test, sample/match and non-match YUFOs were always of the same family and gender. Forty-eight YUFO “individuals” were used in the experiment. Their size and possible viewpoints were the same as for the faces.

2.1.5.3. Scrambled faces. The 48 faces from the face task (shown from the half profile view) were scrambled in MATLAB (MathWorks). A 2-D fast Fourier transform was applied to each face, random phase structure was added, and a 2-D inverse fast Fourier transform was then performed (see e.g. Honey, Kirchner, & VanRullen, 2008). This scrambled face image was considered to have a 0° tilt. The scrambled faces were shown within a circular window with blurred edges (size = 5.9°; Fig. 1). 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 non-match was assigned the original 0° tilt. Every scrambled face was presented on one trial with each of the four possible orientation differences.

2.1.6. ADHD questionnaires

Two self-report questionnaires of attention deficit hyperactivity disorder (ADHD) symptoms (from DSM-IV), were administered in experiment 2 (Magnússon et al., 2006). The first was a self-report of ADHD symptoms experienced in the last six months and the second was a self-report of ADHD symptoms experienced during childhood. Scores range from 0 to 54, with higher scores indicating greater ADHD symptoms. The questionnaires are reliable and valid for ADHD screening (Magnússon et al., 2006). According to Magnússon et al. (2006), the Cronbach‘s alpha for self-reported childhood symptoms was 0.96 for both men and women, and 0.93 and 0.95 for men‘s and women‘s self-reports of current symptoms, respectively. The validity of the questionnaires is also supported by the fact that they predicted diagnoses based on semistructured interviews.

2.1.7. Reading abilities

All participants completed the Adult Reading History Questionnaire (ARHQ-Ice). Participants in experiment 2 were additionally asked to read out loud and in silence.

2.1.7.1. Adult Reading History questionnaire. The Icelandic version of the Adult Reading History Questionnaire (ARHQ-Ice) was used to assess each participant's history of reading difficulties (Bjornsdottir et al., 2013; Lefly & Pennington, 2000). 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. The questionnaire is highly reliable and valid for dyslexia screening (Bjornsdottir et al., 2013). According to Bjornsdottir et al. (2013), Cronbach‘s alpha was 0.92, indicating internal consistency, and test-retest reliability was r = 0.93. ARHQ-Ice scores for adults predicted childhood ICD-10 diagnoses of specific reading disorder, supporting the questionnaire‘s validity.

2.1.7.2. 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). Participants were informed that their reading would be recorded with a microphone, and instructed to read as fast as they could while avoiding errors. One list at a time was placed in front of participants. The number of words read per minute and percentage of correctly read words were the measures of interest.

2.1.7.3. IS-PSEUDO. The IS-PSEUDO reading test was developed to capture an even wider variety of reading abilities (Sigurdardottir et al., 2017). IS-PSEUDO consists of phonologically valid pseudoword forms; reading performance for 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 that the list contained pseudowords, and were instructed to read as fast as they could while minimizing errors. We measured the number of pseudowords read per minute and the percentage of correctly read pseudowords.

2.1.7.4. Silent reading. To assess whether measurements of silent reading speed can reliably differentiate between dyslexic and typical readers, three fairly short Icelandic texts were displayed on a computer screen. An example text was first shown. Participants were instructed to start reading immediately when each text appeared, following an on-screen count-down, and to press a response key as soon as they had finished reading the text.

2.2. Data analysis

During testing, three YUFO trials were found to be defective, as the match and non-match were indistinguishable, and were therefore discarded. Accuracy levels were then calculated from the remaining data. Trials with response times deviating more than three standard deviations from each individual's mean for each subtest (faces, YUFOs, scrambled) were excluded before calculating mean RTs (number of trials in each subtest with extreme RTs in experiment 1: 0–6 per subject; in experiment 2: 0–7 per subject); other trials regardless of accuracy were included. Statistical tests were two-sided with an alpha level of 0.05. Degrees of freedom for t-tests were adjusted if Levene's test revealed unequal variances. Confidence interval level was 95%. Confidence intervals (CI) are marked as CI-BCa when based on bias-corrected and accelerated bootstrapping. CI_{T-D} indicates a confidence interval for the difference in means for typical readers (T) and dyslexic readers (D).

Individual results from experiments 1 and 2 are included as supplementary material (FYS experiment 1 individual results, [dataset] Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018a; FYS experiment 2 individual results, [dataset] Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018b). Trial by trial comparions for face matching (see also Section 3.2.4.7) in experiments 1 and 2 are also included as supplementary material (FYS trial by trial comparison, [dataset] Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018c).

3. Results

3.1. Experiment 1

The mean score on the Adult Reading History Questionnaire (ARHQ-Ice) was 0.36 (SD = 0.15). As Fig. 2 shows, some participants reported little or no history of reading problems, while others reported quite severe reading problems as assessed by ARHQ-Ice. Mean accuracy for face matching on the FYS-test was 85% (SD = 6%) and mean RT was 2702 ms (SD = 687 ms). Multiple regression showed that accuracy and RTs for face matching together explained a significant amount of the variance in scores on ARHQ-Ice ($F(2,36) = 3.328$, $p = 0.047$, $R^2 = 0.156$, $R^2_{adjusted} = 0.109$). Accuracy for face matching ($\beta = -0.402$, CI = [−0.726, −0.077], $p = 0.017$) but not response time ($\beta = 0.026$, CI = [−0.299, 0.350], $p = 0.874$) was a significant independent predictor of scores on the ARHQ-Ice. Lower face matching accuracy predicted a greater history of reading problems (Fig. 2).

3.2. Experiment 2

3.2.1. History of reading problems and current reading ability

Dyslexic readers had significantly higher scores than typical readers

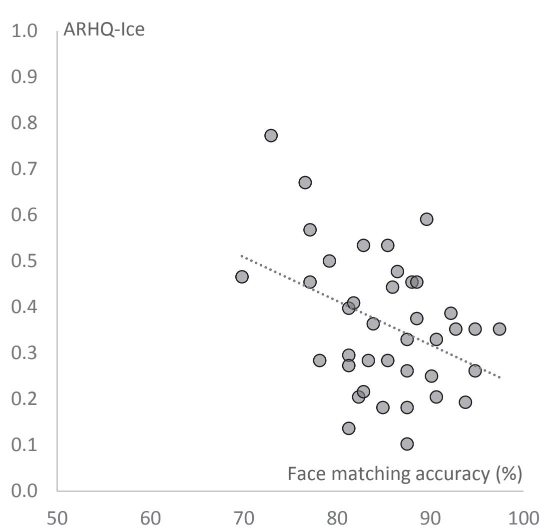

Fig. 2. Face matching accuracy (percent correct) on the FYS-test and scores on the Adult Reading History Questionnaire (ARHQ-Ice) for participants in experiment 1. Face matching accuracy in experiment 1 was significantly negatively correlated with scores on the ARHQ-Ice ($r(37) = -0.394$, CI-BCa = [−0.624, −0.073], $p = 0.013$).

Table 1
Reading abilities of dyslexic and typical reader groups in experiment 2. Significant group differences for particular tests are marked with an asterisk (*).

	Dyslexic (D)		Typical (T)		CI_{T-D}	
	Mean	(S.D.)	Mean	(S.D.)	Lower	Upper
* ARHQ-Ice	0.68	(0.12)	0.34	(0.12)	−0.40	−0.29
* Silent words/min	160	(72)	271	(1 2 1)	61	160
IS-FORM Common						
* Words/min	75	(19)	106	(19)	21	40
* Word acc. (%)	90	(6)	96	(3)	4	8
IS-FORM Uncommon						
* Words/min	47	(15)	71	(14)	17	31
* Word acc. (%)	76	(12)	89	(6)	9	18
IS-PSEUDO						
* Pseudowords/min	35	(12)	51	(12)	11	23
* Pseudoword acc. (%)	63	(17)	82	(8)	12	25

on the ARHQ-Ice, were significantly slower and less accurate than typical readers on the IS-FORM and IS-PSEUDO reading tests, and read significantly fewer words per minute in silence (Table 1; independent samples t-tests, all t's > 4.4, all ps < 0.001). The average reading speed for the IS-FORM common word forms, IS-FORM uncommon word forms, and IS-PSEUDO pseudoword forms will from now on be referred to as "reading speed" (reading speed for silent reading cannot be independently verified and is not included) and the average percent of correctly read (pseudo)word forms from these same reading lists will be referred to as "reading accuracy".

3.2.2. Verification of group assignment

A binary logistic regression with ARHQ-Ice scores, reading speed, and reading accuracy as predictors correctly predicted group membership (whether participants reported being dyslexic or not), in 92.4% of cases (χ^2 (3) = 65.098, $p < 0.001$). Five participants were incorrectly classified, three from the dyslexic reader group (classified as typical readers) and two from the typical reader group (classified as dyslexic readers). One dyslexic reader was classified as "typical" because of fast reading. The participant however had a history of reading problems, as indicated by ARHQ-Ice, and reading accuracy was below the mean for the dyslexic group and worse than every typical reader in our sample. This participant and the matched typical reader were therefore kept in the sample. The other four incorrectly assigned participants were clear borderline cases. They and their matched participants were thus excluded (inclusion of these participants would not change any group differences reported in Fig. 3 from significant to non-significant, or vice versa). All further analyses, unless specifically noted, are restricted to the remaining 58 participants.

3.2.3. ADHD

Eleven dyslexic participants and one typical reader reported a previous ADHD diagnosis. This is representative of dyslexic readers as 18–42% of children with reading disorders also meet diagnostic criteria for ADHD (Germano et al., 2010). Dyslexic participants also had considerably higher scores than typical readers on the ADHD screening test than typical readers for both childhood (dyslexic readers: M = 30, SD = 12; typical readers: M = 13, SD = 8; independent samples t-test, $t(49) = 6.121$, $p < 0.001$, $d = 1.608$, CI_{T-D} = [−22, −11]) and current ADHD symptoms (dyslexic readers: M = 22, SD = 10; typical readers: M = 10, SD = 5; independent samples t-test, $t(41) = 5.983$, $p < 0.001$, $d = 1.571$, CI_{T-D} = [−17, −8]).

3.2.4. Visual tests

3.2.4.1. Simple group comparisons. Fig. 3 shows the results for the three visual tasks (face matching, YUFO matching, and scrambled face matching). No significant group differences in response times were

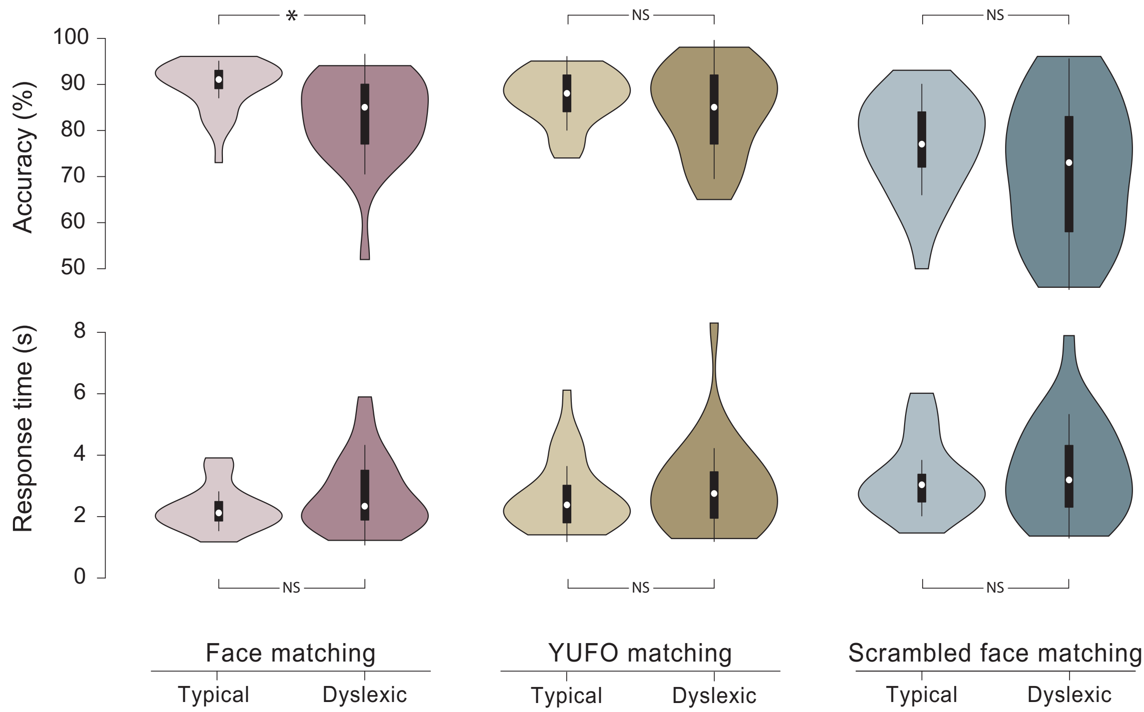

Fig. 3. Matching accuracy (percent correct) and mean response time (seconds) on the FYS-test for typical and dyslexic readers in experiment 2. Significant group differences are marked with an asterisk (*). Non-significant group differences are marked as NS. Chance level is 50% for accuracy. White discs show the medians. Box limits indicate the 25th and 75th percentiles. Whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Polygons represent density estimates of data and extend to extreme values. This violin plot was created with BoxPlotR (Spitzer, Wildenhain, Rappsilber, & Tyers, 2014).

found for any of the three tasks (independent samples t-tests; face matching: $t(46.407) = 1.687$, $p = 0.098$, $d = 0.443$; YUFO matching: $t(56) = 0.806$, $p = 0.424$, $d = 0.212$; scrambled face matching: $t(56) = 0.716$, $p = 0.477$, $d = 0.188$). Compared to typical readers, dyslexic readers were significantly less accurate on face matching (independent samples t-tests; face matching: $t(44.071) = 3.504$, $p = 0.001$, $d = 0.920$; Fig. 3). No other group differences were significant (independent samples t-tests; YUFO matching: $t(46.010) = 1.367$, $p = 0.178$, $d = 0.359$; scrambled face matching: $t(50.004) = 1.703$, $p = 0.095$, $d = 0.447$).

3.2.4.2. Predictions of history of reading problems, reading speed, and reading accuracy. For comparison with experiment 1, a multiple regression was performed with face matching accuracy and response times as predictors and scores on ARHQ-Ice as the dependent variable (ARHQ-Ice model). The two predictors explained a significant amount of the variance in ARHQ-Ice scores ($F(2,55) = 10.970$, $p < 0.001$, $R^2 = 0.285$, $R^2_{adjusted} = 0.259$). Accuracy ($\beta = -0.505$, CI = $[-0.740, -0.269]$, $p < 0.001$) and response times ($\beta = 0.331$, CI = $[0.096, 0.566]$, $p = 0.007$) for face matching were both significant independent predictors of ARHQ-Ice scores: lower accuracy and slower responses were associated with a greater history of reading problems.

Repeating this analysis separately for each group gave non-significant results (dyslexic readers: $F(2,26) = 0.062$, $p = 0.940$, $R^2 = 0.005$, $R^2_{adjusted} = -0.072$; typical readers: $F(2,26) = 1.244$, $p = 0.305$, $R^2 = 0.087$, $R^2_{adjusted} = 0.017$), indicating that the association between face matching performance and ARHQ-Ice scores were driven by group membership (bearing in mind however that ARHQ-Ice scores in each group naturally have a restricted range). Please note that the lack of an association for typical readers is not contrary to the results of experiment 1, as that sample likely consisted of a mixture of typical and dyslexic readers.

We next looked at the association between the performance on the visual tasks included in the FYS-test (response times and accuracy for face matching, YUFO matching, and scrambled face matching) and the three measures of reading performance (ARHQ-Ice, reading speed, and reading accuracy). The results are summarized in Fig. 4.

FYS-test response time measures were not significantly correlated with any measures of reading performance. Face matching accuracy was significantly correlated with all measures of reading performance. Lower accuracy for face matching was associated with a greater history of reading problems, slower reading, and less accurate reading. These results therefore indicate that reading problems are associated with problems in face perception. Accuracy for YUFO matching and scrambled face matching was not significantly correlated with ARHQ-Ice scores or reading speed, but was significantly positively correlated with reading accuracy. Reading problems might therefore also to some extent be associated with more general problems with visual tasks, but these results could also be related to non-perceptual factors, e.g. participants who emphasize accuracy over reading speed might also be the same participants who lay greater emphasis on accuracy over speed in visual tasks.

To increase our understanding of the relationship between performance on visual tasks and reading problems, we calculated partial correlation coefficients between each visual measure and each reading measure, controlling for all other visual measures (e.g. between face RTs and reading accuracy while keeping face accuracy, YUFO RTs, YUFO accuracy, scrambled RTs, and scrambled accuracy constant).

The partial correlation between face matching accuracy and reading speed did not reach significance, nor did the partial correlation between face matching response times and reading speed. The association between face matching accuracy and both ARHQ-Ice and reading accuracy held even when controlling for other visual measures. An additional association between face matching response times and ARHQ-Ice emerged when other visual measures were kept constant. All other things equal, slower face matching was associated with a greater history of reading problems and more errorprone reading. Face matching accuracy and response times thus both explained a unique part of the variance in ARHQ-Ice scores and reading accuracy, not captured by any

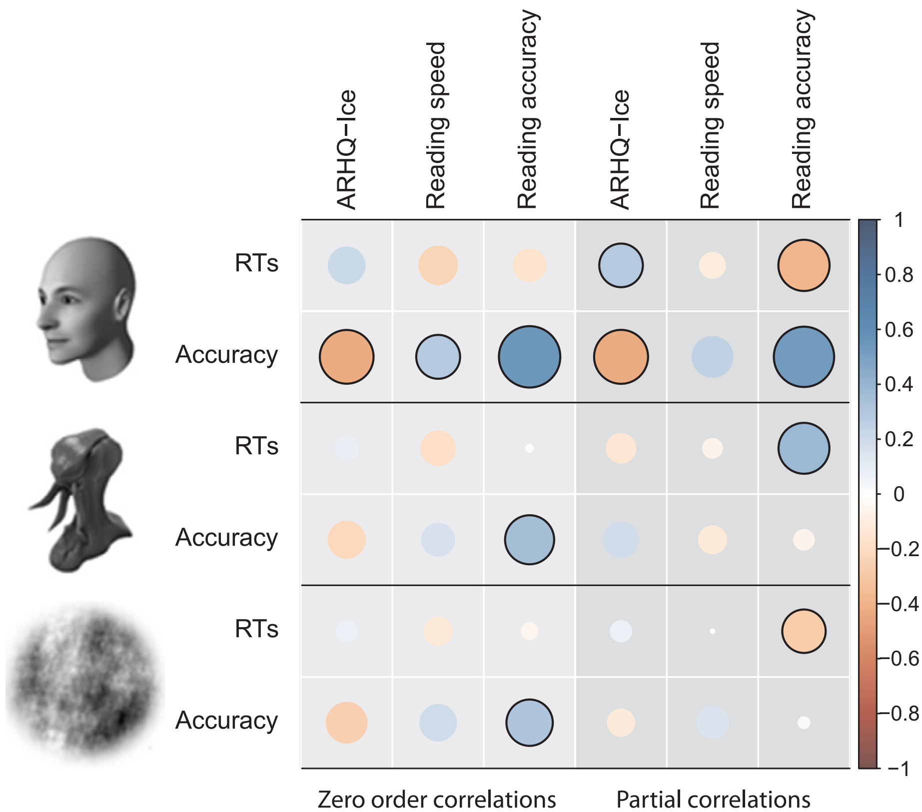

Fig. 4. Association between reading measures and performance on visual tasks (top: face matching; middle: YUFO matching; bottom: scrambled face matching). Areas of circles show absolute values of the corresponding correlation coefficients. Blue shades indicate positive correlations and red shades indicate negative correlations. Black circle outlines indicate a significant correlation. Left panels (light gray) show zero order correlations (Pearson‘s r) between visual measures (response times/RTs and accuracy on the FYS-test) and reading measures. Right panels (dark gray) show partial correlation coefficients between each visual measure and each reading measure, controlling for all other visual measures.

other visual measures.

Neither YUFO matching accuracy nor scrambled face matching accuracy were partially correlated with any reading measures. YUFO matching response times and scrambled face matching response times were not partially correlated with ARHQ-Ice or reading speed. They were, however, partially correlated with reading accuracy, but in different directions. All other things equal, slower scrambled face matching was associated with *less* accurate reading, but slower YUFO matching was associated with *more* accurate reading.

3.2.4.3. Specificity of face discrimination problems in dyslexia. Three hierarchical (sequential) logistic regressions were performed to test whether face matching performance predicted group membership (dyslexic or typical reader) over and above predictions based on performance on the two other visual tasks, as well as over and above predictions based on ADHD diagnosis and symptoms. Accuracy and response times for YUFO matching (YUFO model) and scrambled face matching (scrambled model), respectively, were entered at the first stage of two visual task models. ADHD diagnosis, current ADHD symptoms, and childhood ADHD symptoms were entered at the first stage of the ADHD model. Accuracy and response times for face matching were entered at the second stage of each of the three models.

3.2.4.3.1. YUFO model. The logistic regression model at stage 1 of the YUFO model was not significant, $\chi^2(2) = 3.454$, $p = 0.178$, $R^2_{\mathrm{Nagelkerke}} = 0.077$. Adding accuracy and response times for face matching significantly improved the model (model change: $\chi^2(2) = 19.941$, $p < 0.001$; entire model: $\chi^2(4) = 23.395$, $p < 0.001$). The entire model explained a total of 44% ($R^2_{\mathrm{Nagelkerke}} = 0.443$) of group membership and correctly classified 76% of cases. Face matching accuracy was a significant independent contributor to the model ($p = 0.001$), with lower face matching accuracy associated with increased likelihood of being dyslexic. YUFO matching accuracy ($p = 0.122$), face matching response times ($p = 0.116$) and YUFO matching response times ($p = 0.594$) were not significant independent contributors to the model.

3.2.4.3.2. Scrambled model. The logistic regression model at stage 1 of the scrambled model was significant, $\chi^2(2) = 6.651$, $p = 0.036$. At this stage, the model explained a total of 14% ($R^2_{\mathrm{Nagelkerke}} = 0.144$) of variance in group membership, and correctly classified participants as dyslexic or typical readers in 64% of cases. Accuracy for scrambled face matching was a significant independent predictor ($p = 0.023$), with lower accuracy increasing the likelihood of being dyslexic. Response times for scrambled face matching was a marginally significant independent contributor ($p = 0.066$), with slower responses being associated with greater dyslexia likelihood. Adding face matching accuracy and response times at stage 2 significantly improved the model (model change: χ^2 (2) = 14.288, $p = 0.001$; entire model: $\chi^2(4) = 20.939$, $p < 0.001$). The model now explained 40% ($R^2_{\mathrm{Nagelkerke}} = 0.404$) of group membership variance and correctly classified 78% of cases. Face matching accuracy was now the only significant independent contributor to the model ($p = 0.004$, all other $ps > 0.235$). Lower accuracy for face matching was associated with increased likelihood of being dyslexic.

3.2.4.3.3. ADHD model. The logistic regression model at stage 1 of the ADHD model was significant, χ^2 (3) = 39.660, $p < 0.001$. At this stage, the model explained 66% ($R^2_{\mathrm{Nagelkerke}} = 0.660$) of group membership variance, and correctly classified participants as dyslexic or typical readers in 88% of cases. At stage 1, current ADHD symptoms were the only significant independent contributor to the model (current ADHD symptoms $p = 0.021$; childhood ADHD symptoms $p = 0.057$; ADHD diagnosis $p = 0.191$). The addition of accuracy and response times for face matching significantly improved the model (model change: χ^2 (2) = 12.414, $p = 0.002$; entire model: χ^2 (5) = 52.074, $p < 0.001$), and the predictors in total explained 79% of the variance in group membership ($R^2_{\mathrm{Nagelkerke}} = 0.790$) and correctly classified people as dyslexic or typical readers in 90% of cases. Face matching accuracy ($p = 0.010$) was the only significant independent contributor to the model at this stage (current ADHD symptoms: $p = 0.105$; childhood ADHD symptoms: $p = 0.124$; ADHD diagnosis: $p = 0.305$; face matching response times: $p = 0.110$).

In sum, the hierarchical regression analyses show that face matching predicts dyslexia over and above YUFO matching, scrambled face matching, and the ADHD measures suggesting that face matching performance has specific predictive power for dyslexia independently of any effects of these other factors.

3.2.4.4. Potential violations of assumptions and outliers. In order to increase our confidence in the results of experiment 2, we reanalyzed our data using bias-corrected and accelerated bootstrapping, which is robust to potential violations of assumptions and outliers. Redoing the analyses did not affect the significance of any comparisons in Fig. 3. Similarly, both face matching accuracy and response times were still significant independent predictors of ARHQ-Ice (ARHQ-Ice model). Significance of zero order and partial correlations between reading measures and performance on visual tasks (Fig. 4) did not change, except for the zero order correlation between scrambled face matching accuracy and ARHQ-Ice, which was now significantly different from zero, CI-BCa: $[-0.474, -0.006]$. The significance of independent predictors in the YUFO model was unchanged. The significance of particular predictors in the scrambled model was also unchanged, except for response times for scrambled faces, which changed from marginally significant to significant ($p = 0.047$) at the first stage of the model. Face matching accuracy was still the only significant independent predictor of dyslexia at model stage 2. Significance at stage 1 in the ADHD model was unchanged except for childhood ADHD symptoms which changed from marginally significant to significant ($p = 0.049$); at stage 2, current ADHD symptoms ($p = 0.049$), face matching response times ($p = 0.021$) and face matching accuracy ($p = 0.001$) independently contributed to the model (ADHD childhood symptoms: $p = 0.068$; ADHD diagnosis: 0.057). For unknown reasons, bootstrap estimations failed in 0.05% of iterations in the ADHD model. As a further precaution, we therefore repeated the analysis three times, where ADHD diagnosis (ADHD-diagnosis model), current ADHD symptoms (ADHD-current model), and childhood ADHD symptoms (ADHD-child model) were entered alone at the first stage of each model. Results were comparable; in each case, the model was significant at stage 1, adding face matching accuracy and response time at stage 2 significantly improved each model, and all independent predictors at stage 2 were significant (all *ps* < 0.007) except for face matching response time ($p = 0.138$) in the ADHD-current model.

In sum, reanalyzing all data with a robust bootstrapping method showed that performance on face matching still predicted dyslexia, history of reading problems, and current reading, and that specific visual problems with discriminating faces were found for dyslexic readers.

3.2.4.5. Reliability of visual tests. Fig. 3 shows that there are significant group differences in face matching accuracy but no consistent group differences in response times or accuracy on the other visual tasks. Theoretically, this could occur if dyslexic readers are worse than typical readers on all sorts of tasks, but only the measurements for face matching are reliable enough to reveal a group difference. We therefore looked at the reliability of performance on the visual tasks, both for the entire sample as well as separately for dyslexic and typical readers. As Table 2 shows, response time and accuracy measures for all three visual tasks were highly reliable.

3.2.4.6. Correlations between visual tests. Accuracy measures for faces (F), YUFOs (Y), and scrambled faces (S) were positively correlated (FY: $r(56) = 0.707$; FS: $r(56) = 0.673$; YS: $r(56) = 0.745$; all *ps* < 0.001), indicating that people whose responses were accurate on one FYS task tended to respond accurately on other FYS tasks as well. The same was true for all three response time measures (FY: $r(56) = 0.883$; FS: $r(56) = 0.806$; YS: $r(56) = 0.887$; all *ps* < 0.001), so people who were fast at one FYS task also tended to be fast at other FYS tasks. The FYS accuracy measures shared on average 50% of their variance, and the FYS response time measures shared on average 74% of their variance. While both numbers are relatively high, given the very high reliability of all accuracy measures ($\alpha = 0.91$–0.95) and nearly perfect reliability of all response time measures ($\alpha = 0.98$–0.99), there was still an extensive non-noise portion of performance not shared by the three FYS tasks, i.e. task-specific performance. Judging from our previous analysis, this task-specific performance on the face matching task captures unique variability in group membership, i.e. whether or not people have dyslexia.

Table 2
Cronbach's alpha for the visual tasks (FYS-test) in experiment 2. Reliability estimates were based on all 192 experimental trials of each task.

	Entire sample	Dyslexic Readers	Typical readers
Face matching			
Response times	0.98	0.98	0.98
Accuracy	0.92	0.93	0.84
YUFO matching			
Response times	0.99	0.99	0.99
Accuracy	0.91	0.93	0.84
Scrambled face matching			
Response times	0.99	0.99	0.99
Accuracy	0.95	0.96	0.92

3.2.4.7. Analysis of individual trials. All participants in experiments 1 and 2 compared the same faces, allowing analysis of individual trials. Mean accuracy on each trial (i.e. where a particular sample face, match face, and non-match was shown) across participants in experiment 1 served as "ground truth". A strong positive correlation between this ground truth and average performance levels for these same trials in experiment 2, both for typical readers ($r(190) = 0.727$, $p < 0.001$; Fig. 5) and dyslexic readers ($r(190) = 0.642$, $p < 0.001$; Fig. 5), indicates that some face comparisons were consistently harder than others.

As already established, dyslexic readers were on average less accurate than typical readers at face matching (Fig. 3). However, as the largely parallel fit lines in Fig. 5 show, the group separation did not linearly change with trial difficulty; confirmed by a small and non-

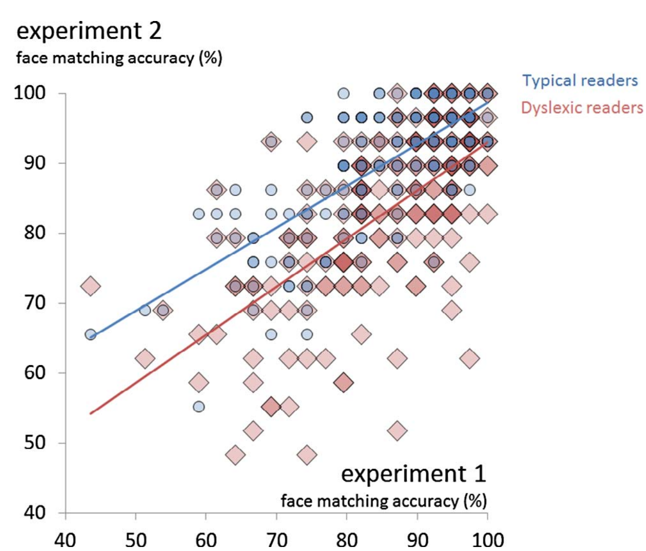

Fig. 5. Trial-by-trial comparison for face matching across experiments. Each data point corresponds to average accuracy (percent correct) on a particular face matching trial (i.e. where a particular sample face, match face, and non-match was shown). The x-axis shows ground truth, or the average accuracy for a particular face matching trial across all participants in experiment 1. The y-axis shows the average accuracy for that same trial across typical readers (circles and best fitting line) and dyslexic readers (diamonds and best fitting line) in experiment 2. Darker markers indicate trials with overlapping values.

significant correlation ($r(190) = -0.118$, $p = 0.102$) between ground truth and typical reader advantage (average typical reader accuracy minus average dyslexic reader accuracy) for the given trial. Note that this is not self-evident; it could for example be that dyslexic readers would be disadvantaged only on particularly challenging face perception tasks, but the disadvantage runs across difficulty levels.

The group separation, however, was greater for trials of medium difficulty, as indicated by a significant curvilinear relationship between ground truth and typical reader advantage ($R^2 = 0.053$, $p = 0.006$). These trials likely stay clear of roof and floor effects, and thus give greater opportunity for detecting group differences. Inclusion of only these trials might suffice to separate typical and dyslexic readers in future studies.

4. Discussion

We administered the same face matching task to a large number of people with and without a history of reading problems. As the task required the discrimination and matching of previously unknown faces across viewpoint, rendered with identical texture, participants were forced to rely on fine-grained visual discrimination of high-level shape cues. In experiment 1, face matching performance was found to predict reading problems in a general sample of university students. In experiment 2 we contrasted face matching performance with other tasks in a sample of matched dyslexic and typical readers. Hierarchical regression analyses showed that difficulties with face matching consistently predicted dyslexia over and above that of matching novel objects (YUFOs) or matching noise patterns that shared low-level visual properties with faces (scrambled faces). Perceptual problems in people with dyslexia were found for an object class with which people have extensive experience, but not for another homogeneous object class with which they have no prior experience, and these problems are unlikely to only reflect deficits in low-level vision. The relationship between dyslexia and face matching problems also could not be accounted for by ADHD measures, making it unlikely that problems with face perception were due to a lack of attention or vigilance.

4.1. Visual problems in dyslexia are specific

In Sigurdardottir et al. (2015), dyslexic readers had problems with face recognition but whether these problems were perceptual or memory-based was unclear. Memory deficits have long been implicated in dyslexia, although most studies have revolved around verbal working memory (de Jong, 1998; Gathercole et al., 2006). The current face matching task involved simultaneously presented faces and thus had minimal working memory and long-term memory requirements, yet a deficit was found for face matching that could not be fully accounted for by performance in the other comparable tasks used here. Memory deficits therefore cannot explain our results.

The current results furthermore show that people with dyslexia have specific visual problems. These problems appear to involve high-level visual cognition instead of being confined to problems with low-level visual mechanisms, although these should not be treated as mutually exclusive. They also show specificity instead of involving only problems with general object perception mechanisms. We speculate that dyslexic readers have specific visual problems with individuating visually homogeneous objects, such as faces and words, with which people have prior experience.

Experience shapes the visual system. High-level ventral stream regions, some of which are known to be hypoactive in dyslexic readers (Richlan et al., 2011), are highly plastic and they likely optimize their responses to effectively solve previously encountered object classification tasks. For example, while neurons in high-level ventral stream regions of macaques respond to several visual stimuli, they carried detailed information on object features most diagnostic for a subordinate-level categorization task on which the monkeys had been trained (Sigala & Logothetis, 2002). This appears to typically happen with reading as well, as certain regions within the ventral visual stream appear to become increasingly optimized for processing words and word-like stimuli as people gain more experience with telling apart different words (for reviews, see e.g. Dehaene & Cohen, 2011; Price & Devlin, 2003; Vogel, Petersen, & Schlaggar, 2013). This experience-dependent specialization is virtually absent in dyslexic readers (van der Mark et al., 2009; Wimmer et al., 2010). Experience with reading may therefore not effectively shape the responses of high-level regions of the ventral visual stream in dyslexic readers. This reduced experience-dependence might generalize to objects other than words. For example, Brachacki, Nicolson, and Fawcett (1995) showed that adults with dyslexia are worse than controls at discriminating between real and fake traffic signs, and while there was a significant correlation between traffic sign recognition and driving experience for controls, dyslexic readers' knowledge of traffic signs improved little with driving experience. We have then recently shown that dyslexic participants have deficiencies in visual statistical learning (Sigurdardottir et al., 2017), which may prevent experience-driven shaping of neuronal responses in the ventral visual stream, which may ultimately hinder visual word and object recognition.

As humans and other primates gain more experience with individuating particular objects, they become increasingly tuned to features or feature dimensions that are diagnostic for telling apart different exemplars of object classes (e.g. Sigala, Gabbiani, & Logothetis, 2002; Sigala & Logothetis, 2002). The learned features or feature dimensions that are useful for telling apart previously experienced exemplars of a trained category (e.g. familiar faces, familiar words) may be useful for distinguishing between new exemplars of that same category (e.g. unfamiliar faces, pseudowords) or exemplars of a different category that shares features with the trained category (e.g. face-like objects, word-like objects). They might however be of limited use when new exemplars of the learned category differ on features or dimensions unlike those deemed diagnostic based on prior experience (e.g. other race faces Meissner & Brigham, 2001) and might be fairly useless for telling apart exemplars of a completely different category (e.g. Yu's Un-Face-like Objects, YUFOs).

It would therefore be of great interest to assess whether differences between the discrimination abilities of dyslexic and typical readers would emerge for YUFO matching following YUFO individuation (expertise) training, especially as individuation training with previously unknown objects is known to engage high-level ventral stream regions (Gauthier et al., 1999; Rossion, Gauthier, Goffaux, Tarr, & Crommelinck, 2002). Such findings would strongly support that the diverging results currently found for YUFOs and faces are not due to the (unavoidable) visual differences in the two object classes, but reflect differences in visual experience.

We should note, at this point, that YUFO matching response times were significantly *positively* correlated with reading accuracy when all other visual measures were kept constant (see partial correlations in Fig. 4). All other things equal, slower YUFO matching was therefore associated with *more* accurate reading. This is somewhat puzzling, especially since dyslexic readers were on average not any better than typical readers at YUFO matching – if anything, the former group was slightly worse (Fig. 3). Similarly, zero order correlations actually indicated that worse performance on all visual tasks was associated with less accurate reading (Fig. 4). While we believe that caution is warranted when interpreting the aforementioned results, as the positive partial correlation between YUFO matching response times and reading accuracy was not predicted *a priori*, it is possible that deficient readers have some task-general problems, leading to slight difficulties with all three visual tasks, as well as some additional task-specific strengths (e.g. visual processing of novel objects) and weaknesses (e.g. visual processing of objects of expertise). This is speculative and would need further testing in future studies.

Assessing whether problems that dyslexic readers have with individuating faces are specific to own-race faces with which people most likely have most experience would be highly interesting. In general, people recognize own-race faces at the subordinate level (i.e. "Anne") while recognizing other-race faces at a more basic level (i.e. "Asian face"), which again is presumed to stem from one's greater experience with faces of a particular race and greater expertise in individuating faces of that race (Lebrecht, Pierce, Tarr, & Tanaka, 2009). Superior memory for same-race versus other-race faces is also significantly correlated with greater left fusiform activity for same-race versus other-race faces (Golby, Gabrieli, Chiao, & Eberhardt, 2001). A reduced or absent other-race effect in dyslexia (i.e. no better performance when recognizing/individuating own-race compared to other-race faces; Megreya, White, & Burton, 2011) would strongly support the role of visual experience in face perception deficits in dyslexia.

We have implicitly assumed that the difference between individuating exemplars of a familiar object class (faces, words) and exemplars of an unfamiliar object class (YUFOs) mainly lies in the nature of their visual representations. Other possibilities certainly exist. Another difference between familiar and unfamiliar objects is semantic knowledge of the objects. When people are trained to associate arbitrary non-visual semantic concepts with particular YUFOs, people have a harder time distinguishing between them on a visual matching task if the YUFOs have been associated with similar as opposed to different concepts (Gauthier et al., 2003). This suggests that semantics can influence visual object recognition. However, while faces in general are associated with more semantic knowledge than YUFOs, both individual faces and individual YUFOs in our study were unfamiliar to our participants. It is therefore unlikely that differences in semantic knowledge for faces and YUFOs are the primary cause of the specificity of the face perception problems observed here.

Scrambled faces share low-level visual properties with non-scrambled faces yet contain no structural object information and are not associated with any particular semantic knowledge. High-level ventral stream regions by definition preferentially respond to intact objects over scrambled objects (e.g. Kourtzi & Kanwisher, 2000; Rossion, Hanseeuw, & Dricot, 2012). While simple group comparisons (Fig. 3) did not reveal any consistent differences between dyslexic and typical readers on the scrambled face matching task, further analysis (see Section 3.2.4.3.2) indicated that this task proved problematic for some dyslexic readers. But note importantly that this same analysis also showed that face matching has additional explanatory power, as it predicts dyslexia over and above any potential explanatory effect of scrambled face matching.

This last point is crucial and deserves further elaboration. We do not make the claim that dyslexia has no relation to visual tasks other than face matching. But even if dyslexic readers as a group have problems with two tasks, and even if these problems are of equal magnitude, this in and of itself says nothing about whether these problems are related. The problems could be (1) completely dependent, so that problems in one task are fully accounted for by problems in the other and vice versa, (2) partially independent, so that some problems are shared by both tasks while some are unique to one or both tasks, or (3) fully independent, so that there could e.g. be two subgroups of dyslexic readers, one of which has problems with one task and another group with problems in the other task.

Our analysis is most consistent with option 2. Dyslexic readers as a group might have some problems with face matching as well as some other visual tasks such as scrambled face matching, but face matching performance explains unique variance in group membership while scrambled face matching and YUFO matching do not. There is indeed something special about face matching, not captured by scrambled face matching or YUFO matching, and face discrimination deficits predict dyslexia over and above discrimination of scrambled faces and novel objects.

Subtle problems with scrambled faces would nonetheless not necessarily go against the possibility that they could stem from functional abnormalities of high-level visual regions. While high-level regions certainly respond more to objects rather than scrambled objects, both word-selective and face-selective regions also appear to be sensitive to low-level visual information (Kay & Yeatman, 2016; Rossion et al., 2012). For example, while the fusiform face area (FFA) responds more to intact faces than intact cars, it also responds more to scrambled faces than to scrambled cars, suggesting that its sensitivity to faces is partly due to low-level visual cues (Rossion et al., 2012). Whether facial perception problems of dyslexic readers are due to problems with specific features of faces, such as those carried by particular orientations or spatial frequency bands, should be established. For example, face detection relies on relatively low spatial frequencies (Owsley & Sloane, 1987) while the individuation of faces primarily relies on intermediate spatial frequencies (Collin, Liu, Troje, McMullen, & Chaudhuri, 2004; Gold, Bennett, & Sekuler, 1999).

There is still a puzzle remaining. In a recent review, Robotham and Starrfelt (2017) conclude that the evidence for a dissociation between face and word processing is stronger in one direction, i.e. while face processing problems might possibly accompany reading deficits, individuals with face processing problems do not consistently show difficulties in reading (see also Burns et al., 2017; Rubino, Corrow, Corrow, Duchaine, & Barton, 2016; Starrfelt et al., 2016). One potential reason, according to Robotham and Starrfelt (2017) is that face recognition may be inherently more challenging than word recognition, but these authors (rightfully) dismiss it as counterintuitive as visual word recognition requires extensive practice. On the other hand, they point out that word processing might compete with face processing for cortical space in the ventral visual stream (see also Dehaene and Cohen (2011)). Word-selective regions, which tend to be less extensive than face-selective regions, partially overlap with face-selective, object-selective, and limb-selective regions of the ventral temporal cortex ((Grill-Spector & Weiner, 2014) but see Harris, Rice, Young, & Andrews, 2016). The opposite is not true, i.e. at least some face-selective regions in the ventral temporal cortex do not consistently overlap with word-selective, object-selective, or limb-selective regions (Grill-Spector & Weiner, 2014). Therefore, if visual word recognition mechanisms are a subset of recognition mechanisms serving other object categories such as faces, but not vice versa, this could lead to the aforementioned asymmetrical patterns of face and word recognition deficits.

What exactly constitutes such mechanisms is a highly interesting question not yet fully resolved. Face recognition might rely on two independent processing modes: holistic and part-based processing (see e.g. DeGutis, Cohan, Mercado, Wilmer, & Nakayama, 2012). Many have argued that a core deficit in acquired prosopagnosia is the failure of holistic processing, and people with developmental prosopagnosia might also show deficits in holistic processing (Avidan, Tanzer, & Behrmann, 2011; DeGutis et al., 2012). Conversely, we recently found that holistic processing of faces appears to be intact in developmental dyslexia (Sigurdardottir et al., 2015). The fact that people with prosopagnosia and dyslexia both show deficits in face processing does by no means suggest that their problems stem from the failure of the same process. It is of great interest whether prosopagnosia and dyslexia are mirror images of one another, with the former primarily characterized by problems with holistic processing (contributing to problems with faces but not words) but the latter by deficits in part-based processing (contributing to problems with faces and words). It remains to be seen whether visual experience (expertise), processing mode (holistic/part-based), or even a combination of both (e.g. part-based expertise) are crucial factors in developmental dyslexia.

It is worth noting that dyslexic readers in our sample, despite their problems with reading and sometimes ADHD, by design attained an education equal to that of their matched typical readers. The dyslexic sample might thus not be representative of the broader dyslexic population. The fact that any group differences are seen even when matching for educational level might however be considered a particular strength of our approach and not a limitation. Dyslexic readers who complete no more than compulsory education could on average be more disadvantaged than those who have higher educational levels, so any sample that also includes the latter group might underestimate true effect sizes. An even stronger association between particular visual measures and reading problems could therefore potentially be seen in a more representative sample.

Finally, it is important to note that the current results do not necessarily contradict other theories of dyslexia. Phonological problems are well documented in dyslexia (Díaz et al., 2012; Pennington et al., 1990), but just as not all dyslexic readers have phonological problems (Valdois et al., 2004), not all dyslexic readers have face perception problems (Fig. 3). More than one factor could contribute to dyslexia, although each factor's relative contribution might vary e.g. depending on the orthographic depth of the language (Icelandic has a relatively shallow orthography). Our results suggest that phonological deficits and face perception deficits are aspects of a more extensive disorder, which ranges from impairments of language to deficits of visual perception.

Conflict of interest

None.

Acknowledgements

This research was funded in part by a postdoctoral grant (Recruitment Fund of the University of Iceland) awarded to Heida Maria Sigurdardottir. Árni Kristjánsson is funded by the Icelandic Research Fund (IRF), the Research Fund at the University of Iceland and the European Research Council (ERC). This research has partly been presented at conferences. We want to thank Dr. Michael J. Tarr for allowing the use of YUFO stimuli in non-profit projects involving scientific research or education (http://wiki.cnbc.cmu.edu/Novel_Objects).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.02.017.

References

Aaron, P. G. (1978). Dyslexia, an imbalance in cerebral information-processing strategies. *Perception and Motor Skills, 47*(3 Pt 1), 699–706.
Avidan, G., Tanzer, M., & Behrmann, M. (2011). Impaired holistic processing in congenital prosopagnosia. *Neuropsychologia, 49*(9), 2541–2552.
Behrmann, M., & Plaut, D. C. (2012). Bilateral hemispheric processing of words and faces: Evidence from word impairments in prosopagnosia and face impairments in pure alexia. *Cerebral Cortex, 24*, 1102–1118.
Benton, A. L., Sivan, A. B., Hamsher, K. D. S., Varney, N. R., & Spreen, O. (1978). *Facial recognition: Stimulus and multiple choice pictures.* New York: Oxford University Press.
Bjornsdottir, G., Halldorsson, J. G., Steinberg, S., Hansdottir, I., Kristjansson, K., Stefansson, H., & Stefansson, K. (2013). The Adult Reading History Questionnaire (ARHQ) in Icelandic: Psychometric properties and factor structure. *Journal of Learning Disabilities, 47*(6), 532–542.
Boucher, J., & Lewis, V. (1992). Unfamiliar face recognition in relatively able autistic children. *Journal of Child Psychology and Psychiatry, 33*(5), 843–859.
Brachacki, G. W., Fawcett, A. J., & Nicolson, R. I. (1994). Adults with dyslexia have a deficit in voice recognition. *Perceptual and Motor Skills, 78*(1), 304–306.
Brachacki, G. W., Nicolson, R. I., & Fawcett, A. J. (1995). Impaired recognition of traffic signs in adults with dyslexia. *Journal of Learning Disabilities, 28*(5), 297–302.
Burns, E. J., Bennetts, R. J., Bate, S., Wright, V. C., Weidemann, C. T., & Tree, J. J. (2017). Intact word processing in developmental prosopagnosia. *Scientific Reports, 7*, 1683.
Catts, H. W. (1989). Defining dyslexia as a developmental language disorder. *Annals of Dyslexia, 39*(1), 50–64.
Collin, C. A., Liu, C. H., Troje, N. F., McMullen, P. A., & Chaudhuri, A. (2004). Face recognition is affected by similarity in spatial frequency range to a greater degree than within-category object recognition. *Journal of Experimental Psychology: Human Perception and Performance, 30*(5), 975–987.
Cox, D. D. (2014). Do we understand high-level vision? *Current Opinion in Neurobiology, 25*, 187–193.
DiCarlo, J. J., & Cox, D. D. (2007). Untangling invariant object recognition. *Trends in Cognitive Sciences, 11*(8), 333–341.
de Jong, P. F. (1998). Working memory deficits of reading disabled children. *Journal of Experimental Child Psychology, 70*(2), 75–96.
DeGutis, J., Cohan, S., Mercado, R. J., Wilmer, J., & Nakayama, K. (2012). Holistic processing of the mouth but not the eyes in developmental prosopagnosia. *Cognitive Neuropsychology, 29*(5–6), 419–446.
Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences, 15*(6), 254–262.
Díaz, B., Hintz, F., Kiebel, S. J., & von Kriegstein, K. (2012). Dysfunction of the auditory thalamus in developmental dyslexia. *Proceedings of the National Academy of Sciences, 109*(34), 13841–13846.
Dundas, E. M., Plaut, D. C., & Behrmann, M. (2013). The joint development of hemispheric lateralization for words and faces. *Journal of Experimental Psychology: General, 142*(2), 348–358.
Gabay, Y., Dundas, E., Plaut, D., & Behrmann, M. (2017). Atypical perceptual processing of faces in developmental dyslexia. *Brain and Language, 173*, 41–51.
Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A.-M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology, 93*(3), 265–281.
Gauthier, I., Anderson, A. W., Tarr, M. J., Skudlarski, P., & Gore, J. C. (1997). Levels of categorization in visual recognition studied using functional magnetic resonance imaging. *Current Biology, 7*(9), 645–651.
Gauthier, I., James, T. W., Curby, K. M., & Tarr, M. J. (2003). The influence of conceptual knowledge on visual discrimination. *Cognitive Neuropsychology, 20*(3–6), 507–523.
Gauthier, I., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (1999). Activation of the middle fusiform 'face area' increases with expertise in recognizing novel objects. *Nature Neuroscience, 2*(6), 568–573.
Germano, E., Gagliano, A., & Curatolo, P. (2010). Comorbidity of ADHD and dyslexia. *Developmental Neuropsychology, 35*(5), 475–493.
Golby, A. J., Gabrieli, J. D., Chiao, J. Y., & Eberhardt, J. L. (2001). Differential responses in the fusiform region to same-race and other-race faces. *Nature Neuroscience, 4*(8), 845–850.
Gold, J., Bennett, P. J., & Sekuler, A. B. (1999). Identification of band-pass filtered letters and faces by human and ideal observers. *Vision Research, 39*(21), 3537–3560.
Grill-Spector, K., & Weiner, K. S. (2014). The functional architecture of the ventral temporal cortex and its role in categorization. *Nature Reviews Neuroscience, 15*(8), 536–548.
Haist, F., Lee, K., & Stiles, J. (2010). Individuating faces and common objects produces equal responses in putative face-processing areas in the ventral occipitotemporal cortex. *Frontiers in Human Neuroscience, 4*, 181.
Harris, R. J., Rice, G. E., Young, A. W., & Andrews, T. J. (2016). Distinct but overlapping patterns of response to words and faces in the fusiform gyrus. *Cerebral Cortex, 26*(7), 3161–3168.
Holmes, D. R., & McKeever, W. F. (1979). Material specific serial memory deficit in adolescent dyslexics. *Cortex, 15*(1), 51–62.
Honey, C., Kirchner, H., & VanRullen, R. (2008). Faces in the cloud: Fourier power spectrum biases ultrarapid face detection. *Journal of Vision, 8*(12), 9 9-9.
Jemel, B., Mottron, L., & Dawson, M. (2006). Impaired face processing in autism: Fact or artifact? *Journal of Autism and Developmental Disorders, 36*(1), 91–106.
Kay, K., & Yeatman, J. (2016). Bottom-up and top-down computations in high-level visual cortex. *bioRxiv*, 053595.
Korinth, S. P., Sommer, W., & Breznitz, Z. (2012). Does silent reading speed in normal adult readers depend on early visual processes? Evidence from event-related brain potentials. *Brain and Language, 120*(1), 15–26.
Kourtzi, Z., & Kanwisher, N. (2000). Cortical regions involved in perceiving object shape. *Journal of Neuroscience, 20*(9), 3310–3318.
Lebrecht, S., Pierce, L. J., Tarr, M. J., & Tanaka, J. W. (2009). Perceptual other-race training reduces implicit racial bias. *PLoS one, 4*(1), e4215.
Lefly, D. L., & Pennington, B. F. (2000). Reliability and validity of the Adult Reading History Questionnaire. *Journal of Learning Disabilities, 33*(3), 286–296.
Liberman, I. Y., Mann, V. A., Shankweiler, D., & Werfelman, M. (1982). Children's memory for recurring linguistic and nonlinguistic material in relation to reading ability. *Cortex, 18*(3), 367–375.
Magnússon, P., Smári, J., Sigurðardóttir, D., Baldursson, G., Sigmundsson, J., Kristjánsson, K., ... Guðmundsson, Ó.Ó. (2006). Validity of self-report and informant rating scales of adult ADHD symptoms in comparison with a semistructured diagnostic interview. *Journal of Attention Disorders, 9*(3), 494–503.
Megreya, A. M., White, D., & Burton, A. M. (2011). The other-race effect does not rely on memory: Evidence from a matching task. *The Quarterly Journal of Experimental Psychology, 64*(8), 1473–1483.
Meissner, C. A., & Brigham, J. C. (2001). Thirty years of investigating the own-race bias in memory for faces: A meta-analytic review. *Psychology, Public Policy, and Law, 7*(1), 3–35.
Owsley, C., & Sloane, M. E. (1987). Contrast sensitivity, acuity, and the perception of 'real-world' targets. *British Journal of Ophthalmology, 71*(10), 791–796.
Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods, 162*(1–2), 8–13.
Pennington, B. F., Orden, G. C., Smith, S. D., Green, P. A., & Haith, M. M. (1990). Phonological processing skills and deficits in adult dyslexics. *Child Development, 61*(6), 1753–1778.
Pontius, A. A. (1976). Dyslexia and specifically distorted drawings of the face: A new subgroup with prosopagnosia-like signs. *Experientia, 32*(11), 1432–1435.
Pontius, A. A. (1983). Links between literacy skills and accurate spatial relations in representations of the face: Comparison of preschoolers, school children, dyslexics, and mentally retarded. *Perception and Motor Skills, 57*(2), 659–666.
Price, C. J., & Devlin, J. T. (2003). The myth of the visual word form area. *NeuroImage, 19*(3), 473–481.

Rack, J. P., Snowling, M. J., & Olson, R. K. (1992). The nonword reading deficit in developmental dyslexia: A review. *Reading Research Quarterly,* 29–53.
Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126*(4), 841–865.
Rhodes, G., Byatt, G., Michie, P. T., & Puce, A. (2004). Is the fusiform face area specialized for faces, individuation, or expert individuation? *Journal of Cognitive Neuroscience, 16*(2), 189–203.
Richlan, F., Kronbichler, M., & Wimmer, H. (2011). Meta-analyzing brain dysfunctions in dyslexic children and adults. *NeuroImage, 56*(3), 1735–1742.
Richler, J. J., Wilmer, J. B., & Gauthier, I. (2017). General object recognition is specific: Evidence from novel and familiar objects. *Cognition, 166*, 42–55.
Robotham, R. J., & Starrfelt, R. (2017). Face and word recognition can be selectively affected by brain injury or developmental disorders. *Frontiers in Psychology, 8*, 1547.
Rossion, B., Gauthier, I., Goffaux, V., Tarr, M. J., & Crommelinck, M. (2002). Expertise training with novel objects leads to left-lateralized facelike electrophysiological responses. *Psychological Science, 13*(3), 250–257.
Rossion, B., Hanseeuw, B., & Dricot, L. (2012). Defining face perception areas in the human brain: A large-scale factorial fMRI face localizer analysis. *Brain and Cognition, 79*(2), 138–157.
Rubino, C., Corrow, S. L., Corrow, J. C., Duchaine, B., & Barton, J. J. (2016). Word and text processing in developmental prosopagnosia. *Cognitive Neuropsychology, 33*(5–6), 315–328.
Rüsseler, J., Johannes, S., & Münte, T. F. (2003). Recognition memory for unfamiliar faces does not differ for adult normal and dyslexic readers: An event-related brain potential study. *Clinical Neurophysiology, 114*(7), 1285–1291.
Schultz, R. T. (2005). Developmental deficits in social perception in autism: The role of the amygdala and fusiform face area. *International Journal of Developmental Neuroscience, 23*(2), 125–141.
Shaywitz, S. E. (1998). Dyslexia. *New England Journal of Medicine, 338*(5), 307–312.
Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry, 57*(11), 1301–1309.
Sigala, N., Gabbiani, F., & Logothetis, N. (2002). Visual categorization and object representation in monkeys and humans. *Journal of Cognitive Neuroscience, 14*(2), 187–198.
Sigala, N., & Logothetis, N. K. (2002). Visual categorization shapes feature selectivity in the primate temporal cortex. *Nature, 415*(6869), 318–320.
Sigurdardottir, H. M., Danielsdottir, H. B., Gudmundsdottir, M., Hjartarson, K. H., Thorarinsdottir, E. A., & Kristjánsson, Á. (2017). Problems with visual statistical learning in developmental dyslexia. *Scientific Reports, 7*(1), 606.
Sigurdardottir, H. M., Fridriksdottir, L. E., Gudjonsdottir, S., & Kristjánsson, Á. (2018a). FYS experiment 1 individual results. Repository: Cognition supplementary material. Version: 1.0. Global persistent identifier: To be determined.
Sigurdardottir, H. M., Fridriksdottir, L. E., Gudjonsdottir, S., & Kristjánsson, Á. (2018b). FYS experiment 2 individual results. Repository: Cognition supplementary material. Version: 1.0. Global persistent identifier: To be determined.
Sigurdardottir, H. M., Fridriksdottir, L. E., Gudjonsdottir, S., & Kristjánsson, Á. (2018c). FYS trial by trial comparison. Repository: Cognition supplementary material. Version: 1.0. Global persistent identifier: To be determined.
Sigurdardottir, H. M., & Gauthier, I. (2015). Expertise and object recognition. In A. W. Toga (Vol. Ed.), *Brain mapping: An encyclopedic reference: Vol. 2*, (pp. 523–527). San Diego, CA, USA: Elsevier/Academic Press.
Sigurdardottir, H. M., Ívarsson, E., Kristinsdóttir, K., & Kristjánsson, Á. (2015). Impaired recognition of faces and objects in dyslexia: Evidence for ventral stream dysfunction? *Neuropsychology, 29*(5), 739–750.
Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: The evidence from contrast sensitivity. *Vision Research, 40*(1), 111–127.
Smith-Spark, J. H., & Moore, V. (2009). The representation and processing of familiar faces in dyslexia: Differences in age of acquisition effects. *Dyslexia, 15*(2), 129–146.
Spitzer, M., Wildenhain, J., Rappsilber, J., & Tyers, M. (2014). BoxPlotR: A web tool for generation of box plots. *Nature Methods, 11*(2), 121–122.
Starrfelt, R., Klargaard, S. K., Petersen, A., & Gerlach, C. (2016). Are reading and face processing related? An investigation of reading in developmental prosopagnosia. bioRxiv, 039065.
Stein, J., & Walsh, V. (1997). To see but not to read: The magnocellular theory of dyslexia. *Trends in Neurosciences, 20*(4), 147–152.
Tarkiainen, A., Helenius, P., & Salmelin, R. (2003). Category-specific occipitotemporal activation during face perception in dyslexic individuals: An MEG study. *NeuroImage, 19*(3), 1194–1204.
Tranel, D., Damasio, A. R., & Damasio, H. (1988). Intact recognition of facial expression, gender, and age in patients with impaired recognition of face identity. *Neurology, 38*(5), 690–696.
Ulfarsson, M. O., Walters, G. B., Gustafsson, O., Steinberg, S., Silva, A., Doyle, O. M., ... Stefansson, K. (2017). 15q11. 2 CNV affects cognitive, structural and functional correlates of dyslexia and dyscalculia. *Translational Psychiatry, 7*(4), e1109.
Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia, 10*(4), 339–363.
van der Mark, S., Bucher, K., Maurer, U., Schulz, E., Brem, S., Buckelmuller, J., ... Brandeis, D. (2009). Children with dyslexia lack multiple specializations along the visual word-form (VWF) system. *NeuroImage, 47*(4), 1940–1949.
Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*(1), 2–40.
Vogel, A. C., Petersen, S. E., & Schlaggar, B. L. (2013). The VWFA: It's not just for words anymore. *Frontiers in Human Neuroscience, 8*, 88.
Wimmer, H., Schurz, M., Sturm, D., Richlan, F., Klackl, J., Kronbichler, M., & Ladurner, G. (2010). A dual-route perspective on poor reading in a regular orthography: An fMRI study. *Cortex, 46*(10), 1284–1298.
Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L., ... Blomert, L. (2010). Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. *Psychological Science, 21*(4), 551–559.