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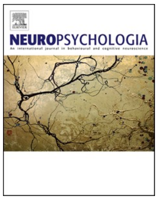

Featural and configural processing of faces and houses in matched dyslexic and typical readers☆

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ABSTRACT

While dyslexia is typically described as a phonological deficit, recent evidence suggests that ventral stream regions, important for visual categorization and object recognition, are hypoactive in dyslexic readers who might accordingly show visual recognition deficits. By manipulating featural and configural information of faces and houses, we investigated whether dyslexic readers are disadvantaged at recognizing certain object classes or using particular visual processing mechanisms. Dyslexic readers found it harder to recognize objects (houses), suggesting that visual problems in dyslexia are not completely domain-specific. Face recognition accuracy was equivalent in the two groups. Lower recognition accuracy for houses was also related to reading difficulties even when accuracy for faces was kept constant, which could indicate a specific relationship between visual word processing and visual processing of non-face objects. Representational similarity analyses (RSA) revealed that featural and configural processes were clearly separable in typical readers, which was not the case for dyslexic readers who appear to rely on a single process. This was not restricted to particular visual categories, occurring for both faces and houses. We speculate that reading deficits in some dyslexic readers reflect their reliance on a single process for object recognition.

1. Introduction

Developmental dyslexia is a reading disorder that occurs despite normal intellectual capacity, adequate educational opportunities and intact sensory abilities (Shaywitz, 1998). A century ago, developmental dyslexia was considered a visual memory deficit (Hinshelwood, 1896; Morgan, 1896). In the 1970s, the focus of dyslexia research moved from visual deficits to impaired phonological processing (Vellutino et al., 2004). While phonological impairments should not be underestimated, the role of phonological factors in reading depends on the orthographic depth of languages and is less important in transparent orthographies (Norton et al., 2015; Ziegler et al., 2010). More recently, evidence has accumulated for temporal, motor, attentional, auditory, and visual dysfunction in dyslexia (De Martino et al., 2001; Farmer and Klein, 1995; Giofrè et al., 2019; Goswami, 2011; Norton et al., 2015; Reid, 2018; Valdois et al., 2004; Ziegler et al., 2010) suggesting that dyslexia is a heterogeneous deficit.

Researchers continue to debate whether dyslexic readers have difficulties with high-level visual processing and, if so, whether their problem is limited to specific visual categories or processes. Recent behavioral and neuroscientific research suggests that dyslexic readers have problems with high-level visual processing (Collins et al., 2017; Gabay et al., 2017; Sigurdardottir; Arnardottir et al., 2019; Sigurdardottir et al., 2018; Sigurdardottir et al., 2015). High-level vision is typically considered to involve later stages of the ventral visual stream that analyze the physical properties of objects and surfaces in the environment. Low-level vision refers to earlier visual stages and is characterized by processing physical properties of the retinal image (Cox, 2014).

A meta-analysis of functional imaging studies of reading and reading-related tasks in children and adults with dyslexia uncovered hypoactivity of high-level ventral stream regions – in or close to the left fusiform gyrus (Richlan et al., 2011). Notably, these hypoactive regions seem to partly correspond to the so-called visual word form area (VWFA, see e.g. Cohen et al., 2002; Dehaene and Cohen, 2007, 2011), potentially reflecting a visual recognition deficit for words. These areas – including the VWFA – are however not only activated during visual word tasks but also during different types of visual object tasks (Price and Devlin, 2003;

☆ Featural versus configural processing in dyslexia.

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Starrfelt and Gerlach, 2007; Vogel et al., 2014). Therefore, potential visual recognition deficits in dyslexic readers might be restricted to visual words (Domain-specific; Fig. 1A) or generalize across categories (Domain-general; Fig. 1B). Domain-specific accounts assume that specialized cognitive functions support the processing of specific types of visual stimuli (Kanwisher, 2000; Rhodes et al., 2004; Yovel and Kanwisher, 2004) such as words, faces or places. Domain-general accounts postulate that general mechanisms operate on several visual categories but to different degrees (Behrmann and Plaut, 2013; Gauthier et al., 2014; Hills et al., 2015; Rice et al., 2020).

Face processing has been at the center of the domain generality/specificity debate. If face processing requires domain-specific mechanisms (e.g. Kanwisher, 2000; Rhodes et al., 2004; Yovel and Kanwisher, 2004) then visual word processing problems in dyslexia should be completely independent of any problems in face processing (see Robotham and Starrfelt, 2017); word processing deficits could however generalize to other non-face objects if visual words do not depend on domain-specific mechanisms (Fig. 1C). According to other accounts, word processing problems in dyslexia should specifically generalize to faces, as these accounts postulate a mutual structural and functional dependency of faces and words through specific restrictions on neural and cognitive development (Fig. 1D; Behrmann and Plaut, 2019; Dehaene et al., 2010; Plaut and Behrmann, 2011). Additionally, both words and faces are objects of expertise (e.g. Gauthier and Nelson, 2001; Gauthier et al., 2000; Ventura et al., 2019; Wong and Gauthier, 2007) and problems with gaining visual expertise in dyslexia could lead to specific connections between word and face processing (Lieder et al., 2019; Sigurdardottir et al., 2017; but see Sigurdardottir, Hjartarson, et al., 2019). This would predict a specific deficiency for word and face processing but not for other visual categories in dyslexia (Fig. 1D).

Several studies have found no significant differences in the performance of dyslexic and typical readers in face recognition (Brachacki et al., 1994; Holmes and McKeever, 1979; Rüsseler et al., 2003). Although Smith- Spark and Moore (2009) found no overall differences in naming speed or accuracy for familiar faces between dyslexic and typical readers, they discovered that typical readers were faster at naming familiar faces that they learnt earlier in life than dyslexic readers. Several other studies have on the other hand reported face processing problems for dyslexic readers (Collins et al., 2017; Gabay et al., 2017; Sigurdardottir; Arnardottir et al., 2019; Sigurdardottir et al., 2018; Sigurdardottir et al., 2015). Additionally, more general visual recognition problems for dyslexic readers have been found. Sigurdardottir et al. (2015) reported difficulties in recognizing exemplars of other complex non-word familiar visual categories such as different birds, butterflies, cars, houses, or planes. Brachacki et al. (1995) found that adults with dyslexia were worse than typical readers at distinguishing between real and fake traffic signs. Huestegge et al. (2014) also reported more detail-related errors in visual long-term memory of children with dyslexia than their matched controls. However, Gabay et al. (2017) and Sigurdardottir et al. (2018) did not observe object recognition deficits for dyslexic readers for cars and novel objects. The results from the current literature is therefore mixed.

1.1. *Differences in processing?*

One potential reason for the mixed findings is that visual problems in dyslexia are process-specific, and some tasks may specifically tap into a visual process that is deficient in dyslexic readers. Featural and configural processing have been identified as separable approaches to visual recognition (Lobmaier et al., 2010; Rossion et al., 2000), and it is possible that dyslexic readers have a deficiency in one but not the other. The term 'featural processing' refers to the processing of the basic

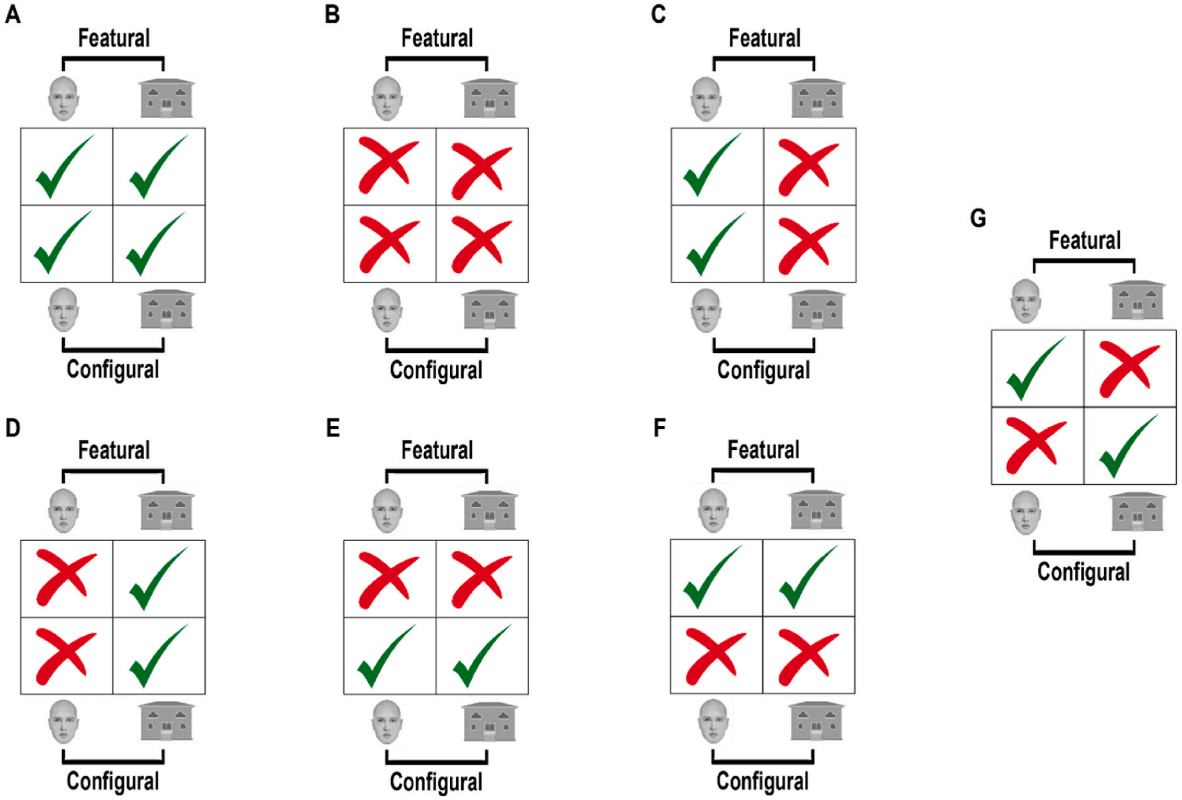


Fig. 1. A visual summary of possibilities regarding featural or configural processing of faces and houses in dyslexic readers. A. Domain-specific; B. Domain-general; C. Deficit for non-face objects; D. Deficit for objects of expertise, or for faces and words as a result of mutual structural and functional dependency of these two categories; E. Process-specificity in featural processing difficulty; F. Process-specificity in configural processing difficulty; G. Process-specificity in the process most important for recognizing objects of a particular visual category. Checks indicate intact abilities, whereas crosses indicate deficient abilities.

features of a stimulus (e.g., letters in a word) while ‘configural processing’ involves encoding or interpreting associations between the features of a stimulus (Maurer et al., 2002). Three types of configural processing have been described: (1) first order relations – referring to the basic configuration of features (e.g., the relative position of letters in a word); (2) second-order relations – perceiving the spatial relationship among features (e.g., distance between letters); and (3) holistic processing – perceiving the features as a Gestalt (e.g., compulsory attention to all parts of a word) (Maurer et al., 2002; Roberts et al., 2015).

Featural processing is generally assumed to be important for word recognition (Farah et al., 1998; Martelli et al., 2005; Pelli et al., 2003) while configural processing is often considered the hallmark of face processing (McKone et al., 2007) and less important for word recognition (Farah et al., 1998). Sigurdardottir et al. (2015) demonstrated intact holistic processing of faces in dyslexic readers. As face and object recognition problems for dyslexic readers were still found, this may reflect problems with featural processing in dyslexia. If dyslexia is process-specific, difficulties with featural processing of non-word objects (regardless of object category) would be expected as word processing is assumed to depend predominantly on featural information (Fig. 1E). Interestingly, Sigurdardottir, Arnardottir, et al. (2019) found that dyslexic readers had problems with featural processing of faces while global form processing of faces – likely reflecting configural processing – was intact. Tso et al. (2020) found that dyslexic readers had stronger holistic processing and weaker left side biases for Chinese characters than controls. As expertise in Chinese characters is associated with decreased holistic processing and a stronger left side bias (an indication of right hemisphere lateralization; Hsiao and Cottrell, 2009; Tso et al., 2014), Tso et al. (2014) proposed that the right hemisphere can engage in either holistic or part-based/featural processing based on task demands, and that dyslexic readers might have a problem with right hemisphere featural processing.

Gaining visual expertise with a category is however more often associated with increased configural processing for the category (e.g. Bukach et al., 2006; Gauthier and Bukach, 2007; Gauthier and Tarr, 2002; but see McKone and Robbins, 2007). Wong et al. (2011, 2019) found that word recognition in expert readers is comparable to other domains of perceptual expertise as it relies on configural processing. Configural processing of words is involved in fast parallel reading (Ventura et al., 2019) and as reading skills improve, letter-by-letter reading changes to parallel word reading (Grainger et al., 2012; Grainger and Ziegler, 2011). With improved reading abilities, the VWFA also becomes more sensitive to common combinations of letters, presumably reflecting reading expertise (Binder et al., 2006). Wong et al. (2011) showed that word processing is more likely to be configural for native than second-language readers, and for words compared to pseudowords. Visual recognition deficits in dyslexia may therefore also manifest as impairments in fast and accurate configural processing of words and objects (Fig. 1F).

The literature on featural vs. configural processing is dyslexia is somewhat mixed. For example, Brady et al. (2020) suggested that dyslexia is associated with increased configural (holistic) processing of words, while Conway et al. (2017) suggested that holistic word processing in dyslexia is impaired and that dyslexic readers may read more analytically than typical readers. Franceschini et al. (2017) also found that while typical readers process global or configural information before local or featural information, dyslexic children prioritize local processing above global processing. Franceschini et al. (2017) also reported that a lack of normal hierarchical global-to-local visual processing in pre-readers is predictive of future reading problems (see also Franceschini et al., 2021).

Potential configural processing deficits in dyslexic readers can possibly be attributed to their difficulty with acquiring expertise, as studies have shown that dyslexic readers have a problem with visual learning (e.g. Lieder et al., 2019; Sigurdardottir et al., 2017; but see Brachacki et al., 1995; Sigurdardottir, Hjartarson, et al., 2019). However, configural processing may not be a marker of general visual expertise and how expertise impacts different processes could depend on how much information each process conveys (Hsiao and Cottrell, 2009; Zhang et al., 2005) and on task demands (Zhou et al., 2012). Expertise may only lead to enhanced processing of configurations if this is the most diagnostic information for identity. When features are crucial for recognition, then expertise may improve the efficiency of featural processing for those categories. Zhou et al. (2012), for instance, found that art students who are experts in face drawing have decreased holistic face processing, since when art students draw faces, they need to attend to face features. Also, Tso et al. (2014), discovered that Chinese readers with limited writing experience had higher holistic processing, but Chinese readers who could write characters fluently had reduced holistic processing, presumably because writing improves the ability to perceive the characters analytically. Therefore, if the process shift is experience-dependent, we may expect dyslexic readers to have problems with processes that are important for that specific category if they have trouble with acquiring visual expertise (Fig. 1, example G). For example, configural processing is dominant for face recognition, therefore dyslexic readers who cannot gain expertise may have limited configural processing abilities for faces.

1.2. Current aims

Given the ambiguity of existing empirical findings, we manipulated configural vs. featural information of two visual categories, faces and houses, to address the following questions: (a) Do dyslexic readers have problems with recognizing non-word visual objects? (b) Are such potential problems specific to particular visual categories (faces or houses)? (c) Are problems in dyslexic readers process-specific (featural or configural)?

2. Method

2.1. Participants

We recruited 68 participants, or 34 pairs matched on gender, age (±5 years), and educational levels. Thirty-four participants reported a previous diagnosis of dyslexia (21 women; mean age: 37.2 years, range 18–62) and 34 were self-reported typical readers (21 women; mean age: 36.8, range 18–67). The stopping rule for data collection was to either test all volunteers for the study up to a limit of 40 matched pairs, or to stop data collection when no new matched pairs could be recruited within a particular extended time period, whichever came first.

In each group, 6 people had completed the first level of schooling (high school), 15 the second level (gymnasium), 8 the third level (undergraduate degree), and 5 had completed the fourth level (graduate degree). All participants reported normal or corrected-to-normal vision. Participants were recruited using varied means, e.g. advertisements on social media and radio. All were native Icelandic speakers. Participants received a gift certificate at a local shopping mall (value: 3000 ISK, approximately $25) for participation.

For our main analyses, three participant pairs were excluded, leaving 31 matched pairs (see section Method: Verification of group classification). With an alpha = .05, power = 0.80, and 31 participants in each group, minimum detectable effect size (MDE) of paired Cohen’s d was 0.52, and MDE of Pearson’s r was 0.35 (GPower 3.1; Faul et al., 2007), considered to be medium effect sizes.

2.2. Procedure

The study was approved by the Icelandic National Bioethics Committee (ID 14–027) and reported to the Icelandic Data Protection Authority. Participants gave their informed consent. The experiment took place in a well-lit and quiet room. All tasks and questionnaires were computerized and presented using PsychoPy (Peirce et al., 2019) on an

Asus monitor (60 Hz, resolution 2560 × 1440 pixels). Viewing distance was approximately 57 cm. The stimuli were presented on a white background. Verbal instructions were prerecorded, and participants were instructed to listen to them attentively.

Participants sat in front of the monitor and started by answering questions about previous diagnoses (including dyslexia, attention deficit hyperactivity disorder (ADHD), dyscalculia, autism, hearing impairment, and language problems other than dyslexia). Dyscalculia and ADHD are two common dyslexia comorbidities (Germanò et al., 2010; Wilson et al., 2015). There is substantial evidence that people with autism have poor face recognition (Griffin et al., 2021), so we wanted to make sure that they were not the driver of the face recognition results of our object recognition task. We asked about hearing impairments as they might possibly affect reading development (Moeller et al., 2007) and understanding of verbal instructions.

Three questionnaires were administered: The Adult Reading History Questionnaire (ARHQ-Ice), and Behavioral Evaluation Questionnaire for Adults I and II. Questions were displayed individually and consecutively, in written form, but were also read to the participants via headphones. Next, participants performed a visual task to measure their configural and featural processing of faces and houses. Following this, they completed a lexical decision task that evaluated the effect of word length (further description and results of this task can be found in Supplementary Materials), and finally, their reading was assessed with the IS-FORM and IS-PSEUDO reading tests.

2.3. *Adult Reading History Questionnaire (ARHQ-Ice)*

The original ARHQ is a 23-item self-report questionnaire (responses made on a 5-point Likert scale) developed by Lefly and Pennington (2000). We used the Icelandic version of the ARHQ (ARHQ-Ice), a valid and reliable test for assessing the reading difficulties of adults (Bjornsdottir et al., 2014). As suggested by Bjornsdottir et al. (2014), question number 15 in the Icelandic version was excluded from analysis because of truncated range. Scores on ARHQ-Ice range from 0 to 1, where higher scores indicate more difficulties in reading. The suggested cut-off score for dyslexia screening is 0.43 or higher (Bjornsdottir et al., 2014).

2.4. *Behavioral Evaluation Questionnaire for adults I and II*

The Behavioral Evaluation Questionnaire for adults I and II was used to evaluate ADHD symptoms according to DSM-IV criteria. These self-report questionnaires are reliable and valid tools for screening for ADHD (Magnússon et al., 2006). After listening to instructions, participants answered questions on a four-point Likert scale. The first questionnaire was used to evaluate ADHD symptoms in the last six months and the second one measured ADHD symptoms during childhood from ages 5–12 years. The total scores on each questionnaire can vary from 0 to 54, where scores above 25.8 on the childhood ADHD measure, and scores above 32.5 on the current ADHD measure, are considered indicators of ADHD.

2.5. *Object recognition task*

The object recognition task was administered to measure featural and second-order configural processing of faces and houses. Second-order configural processing (where second-order relations are manipulated, see section Introduction: Differences in processing?) will from now on be referred to simply as configural processing. Stimuli were part of a larger set with different featural and configural information developed by CollinsZhu et al. (2012); we thank Jane E. Joseph for providing the stimuli). In our task, there were 192 trials for each combination (featural faces, configural faces, featural houses and configural houses).

For each sample face/house image, there was a pair of images: a match and foil. The match was identical to the sample, but the foil was different featurally or configurally with 0, 1, 2 or 3 features/configurations in common with the sample (difficulty level; see Fig. 2). For example, if difficulty level was 1, the sample and foil shared 1 feature (e.g., same eyes or door) or 1 configuration (e.g., same space between eyes or windows) while if difficulty level was 2, they shared 2 features (e.g. identical eyes and nose or identical door and windows) or 2 configurations (e.g. distance between the two eyes, and between the eyes and the nose, or between the two windows, and between the windows and the door).

Participants were asked to respond quickly while minimizing errors. After listening to instructions, participants completed a short practice test followed by the main object recognition task (Fig. 3). Both were two-alternative forced-choice delayed match-to-sample tasks. Trials had the same randomized order for each participant. In the practice test, 20 stimulus-pairs of simple geometrical objects were used (e.g. circle, square), and participants received feedback about the correctness of each response.

Each trial in the main task started with a 500 ms fixation cross at screen center. After the fixation cross disappeared, a sample image (face or house) appeared at screen center for 300 ms followed by a circular random dot mask (~8° in diameter) displayed at the same location for 200 ms. Subsequently, match and foil images appeared simultaneously approximately 3° to the left and right of screen center. Sample images were roughly 4° × 4° while foil and match images were 2.5° × 2.5°. The match and foil images were smaller to minimize the use of low-level template matching. Match and foil images remained onscreen until participants indicated with a button press which image was identical to the sample image. The “Z” button corresponded to the left image and the “M” button to the right image (both marked with yellow stickers). After response, the stimuli disappeared, and the next trial started after a 500 ms inter-trial interval (fixation cross around 0.4° × 0.4°). No feedback was given. After every 50 trials, participants were given a break, and pressed the space bar when ready to continue.

Our main focus was on accuracy even though we additionally assessed reaction times, as previous studies have shown that group differences between dyslexic and typical readers are found for accuracy (Sigurdardottir et al., 2015, 2018).

2.6. *IS-FORM and IS-PSEUDO reading tests*

The IS-FORM and IS-PSEUDO reading tests (Sigurdardottir et al., 2015, 2017) were used to measure reading ability. The tests were computerized and included three lists consisting of 128 common Icelandic word forms, 128 uncommon Icelandic word forms, and 128 pseudowords. Participants were informed by recorded instructions that they had to read the (pseudo)words of each list out loud as fast as possible while keeping errors to a minimum. Participants pressed the space bar and a countdown began, thereafter they read a short practice test out loud. Following this, the researchers left the room, and the three lists were presented consecutively following a countdown in each case, and participants read each list out loud. Two main factors were analyzed in these tests: reading speed (number of words or pseudowords read per minute) and reading accuracy (percentage of correctly read words or pseudowords).

3. Statistical analysis and results

3.1. *Data analysis overview and exclusion/inclusion*

Before calculating mean response times (RTs), trials with RTs deviating by more than three standard deviations from the mean of each participant for each condition of the object recognition task (e.g., featural processing of faces with difficulty level of 1) and lexical decision task (e.g., 4 letters) were excluded; other trials were included, regardless of accuracy. D_{av} refers to a paired Cohen’s d which is calculated as the difference between the means of each group, all divided by the standard

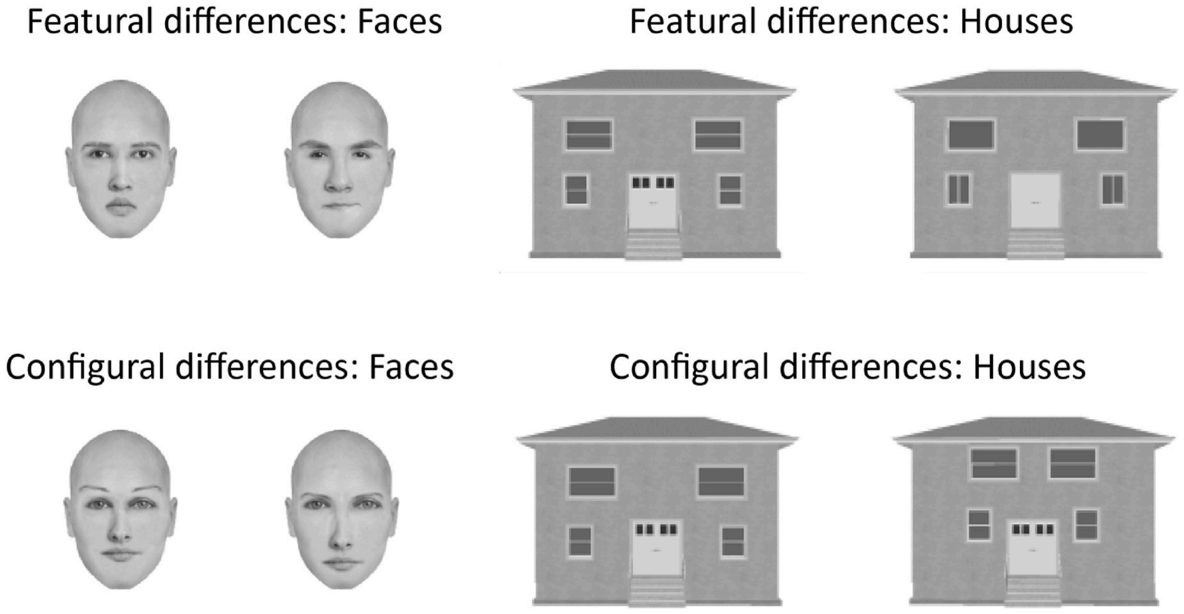


Fig. 2. Examples of faces and houses with no common features or configurations (difficulty level: 0 shared features/configurations).

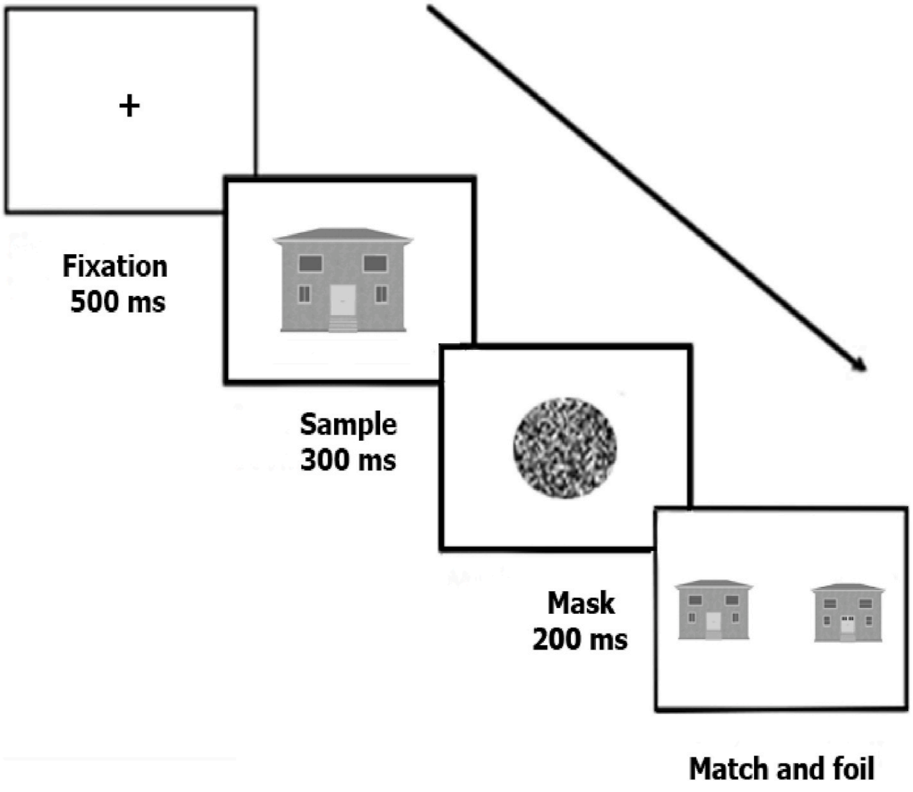


Fig. 3. The experimental design. On each trial, a sample image (face or house) appeared at screen center followed by match and foil images displayed simultaneously to the left and right of screen center. The match image was identical to the sample image, but the foil image was different either featurally or configurally at four possible levels (difficulty levels 0–3). Match and foil images remained onscreen until the participants indicated with a button press which of the images was identical to the sample image.

deviation of the paired difference scores. The paired difference, and thus the D_{av} and the confidence intervals (*CI*), are always based on typical reader scores minus the paired dyslexic reader scores. Due to recording failure, three participants (one dyslexic reader and two typical readers) had missing values for reading speed and accuracy for the IS-FORM lists. To impute the missing values, we first estimated the relationship between ARHQ-Ice and reading speed and accuracy for the IS-FORM/IS-PSEUDO lists from a previous larger independent dataset with linear regression (ARHQ-Ice as an independent variable and reading speed and accuracy as dependent variables). Subsequently, we used the regression coefficients from this regression model to estimate imputed values for missing reading speed and accuracy values of the current study from ARHQ-Ice scores. Average reading speed (words per minute) and average reading accuracy (percent of correctly read words) were then calculated across the three reading lists for each participant. For additional analyses excluding these participants, see Supplementary Information, Correlations of Object Recognition, Reading Speed and Reading Accuracy After Excluding Participants with Missing Reading Scores. ARHQ, reading speed and reading accuracy were used to verify proper group assignment using binary logistic regression, see Results:

Verification of Group Classification. Our main analyses were based on accuracy measures from the object recognition task, and included comparisons of group means, comparison with reading measures, and representational similarity analysis (RSA), as detailed below. Alpha levels were set to 0.05 and all statistical tests were two-sided.

We compared object recognition of matched dyslexic and typical readers with paired t-tests to see whether featural face, featural house, configural face, and configural house accuracy differed between these two groups. Then, we used a 2 × 2 x 2 repeated measures ANOVA to assess any interactions, with group (dyslexic and typical readers), stimulus (faces and houses), and process (featural and configural) as factors, and accuracy of object recognition as the dependent measure. We calculated zero-order correlations to estimate the association between performance on the object recognition task (accuracy for the four subtasks, as well as total accuracy of faces, houses, featural, and configural processing) and the three measures of reading performance (ARHQ-Ice, reading speed, reading accuracy). We additionally calculated partial correlations to estimate the specificity of such associations.

We also used representational similarity analyses (RSA) to compare correlational matrices of object recognition tasks (reference models) to predicted data patterns (conceptual models). Three examples of conceptual models (stimuli, processes, and difficulty levels) are shown in Fig. 7, panel B. The stimuli model will fit the data well if individuals mainly differ in their ability to discriminate/recognize faces vs. houses. The processes model fits the data well if individuals mainly differ in their ability to discriminate/recognize objects by the use of featural vs. configural processing. The difficulty level model will fit the data well if individuals mainly differ in their ability to discriminate/recognize objects of different difficulty levels.

3.2. *Reading ability and history of reading problems*

Dyslexic readers reported a greater history of reading problems than typical readers on the ARHQ-Ice. They also read less accurately and more slowly than typical readers on the IS-FORM and IS-PSEUDO reading tests (Table 1). In what follows, "reading speed" and "reading accuracy" respectively, refer to the average speed, i.e. (pseudo)word forms read per minute regardless of accuracy, and average percent of correctly read (pseudo)word forms across the IS-FORM common word forms, IS-FORM uncommon word forms, and IS-PSEUDO pseudoword forms. For Cumming estimation plot of Reading Speed and Reading Accuracy After Exclusion of Misclassified Participants, see Supplementary figure s8.

3.3. *Verification of group classification*

A binary logistic regression was run with ARHQ-Ice scores, reading speed, and reading accuracy as predictors and group as a dependent variable. The confusion matrix showed that group membership was correctly predicted in 95.6 percent of cases. Three participants were misclassified, one from the dyslexic reader group (classified as a typical reader) and two from the typical reader group (classified as dyslexic readers). They were excluded from the analyses along with their matched participants. After exclusion, 62 participants remained, where thirty-one of them reported a previous diagnosis of dyslexia (19 women; mean age: 36.9 years, range 18–62) and another 31 were self-reported typical readers (19 women; mean age: 36.5, range 18–67). In each group, 5 people had completed the first level of schooling (high school), 14 the second level (gymnasium), 7 the third level (undergraduate degree), and 5 had completed the fourth level (graduate degree). Unless otherwise noted, all further analyses are limited to the remaining 62 participants.

3.4. *Other disorders*

All participants reported normal or corrected-to-normal vision, two dyslexic readers and two typical readers reported hearing impairments, 10 dyslexic readers reported dyscalculia (consistent with previously described co-occurrences of dyslexia and dyscalculia, e.g. Wilson et al., 2015), one dyslexic reader reported an autism spectrum disorder and one reported language problems other than dyslexia. A previous diagnosis of ADHD was reported by 10 dyslexic readers and three typical readers, which is consistent with the well-known connection between dyslexia and ADHD (see e.g. Germanò et al., 2010). Also, in the screening questionnaires for ADHD (Behavioral Evaluation Questionnaire for Adults I and II), 13 dyslexic readers and eight typical readers scored over suggested screening scores on the childhood ADHD measure, and 5 dyslexic readers and 1 typical reader on the current ADHD measure. Dyslexic participants had significantly higher scores than typical readers for both childhood (dyslexic readers: $M = 22.52$, $SD = 15.65$; typical readers: $M = 14.42$, $SD = 13.55$; paired samples t-test, $t(30) = -2.46$, $p = .02$, $D_{av} = -0.55$, 95% CI [−14.81,-1.38]), and current ADHD symptoms (dyslexic readers: $M = 16.68$, $SD = 12.38$; typical readers: $M = 11.16$, $SD = 8.97$; paired samples t-test, $t(30) = -2.10$, $p = .04$, $D_{av} = -0.52$, 95% CI [−10.88, −0.16]).

3.5. *Object recognition task: overall group differences and correlations*

The reaction times of the two groups were comparable (paired samples t-tests, all four subtasks $ps > 0.58$, $D_{avs} > 0.14$), but dyslexic readers were less accurate than matched controls at recognizing houses both featurally and configurally. The dyslexic group was significantly less accurate at featural processing of houses ($M = 75.66\%$, $SD = 5.61\%$) than the typical group ($M = 78.70\%$, $SD = 5.60\%$; $t(30) = 2.13$, $p = .04$, $D_{av} = 0.54$, 95% CI [0.13, 5.96]) as well as at configural processing of houses (dyslexic readers $M = 80.70$, $SD = 7.47$; typical readers $M = 85.13\%$, $SD = 6.75\%$; $t(30) = 2.53$, $p = .02$, $D_{av} = 0.62$, 95% CI [0.86, 8.01]). Notably, however, neither featural nor configural processing of faces differed significantly between the groups (see Fig. 4; featural faces: dyslexic readers $M = 81.23\%$, $SD = 6.61\%$; typical readers $M = 81.97\%$,

Table 1

Descriptive statistics and summary of paired samples t-tests for reading abilities and history of reading problems of dyslexic and typical reader groups. SD = standard deviation.

	Dyslexic		Typical		t (33)	P	D_{av}
	Mean	SD	Mean	SD			
ARHQ-Ice	0.70	0.12	0.32	0.13	−13.18	<.001	−3.04
IS-FORM Common							
Word accuracy (%)	93.66	4.74	96.81	3.56	3.39	.002	0.76
Words/minute	64.49	17.62	100.37	20.43	6.89	<.001	1.88
IS-FORM Uncommon							
Word accuracy (%)	81.35	10.31	94.07	7.09	6.12	<.001	1.46
Words/minute	41.06	12.57	71.76	15.76	9.14	<.001	2.17
IS-PSEUDO							
Pseudoword accuracy (%)	62.77	19.09	86.29	12.74	6.09	<.001	1.48
Pseudowords/minute	31.40	16.09	48.96	13.10	4.55	<.001	1.20

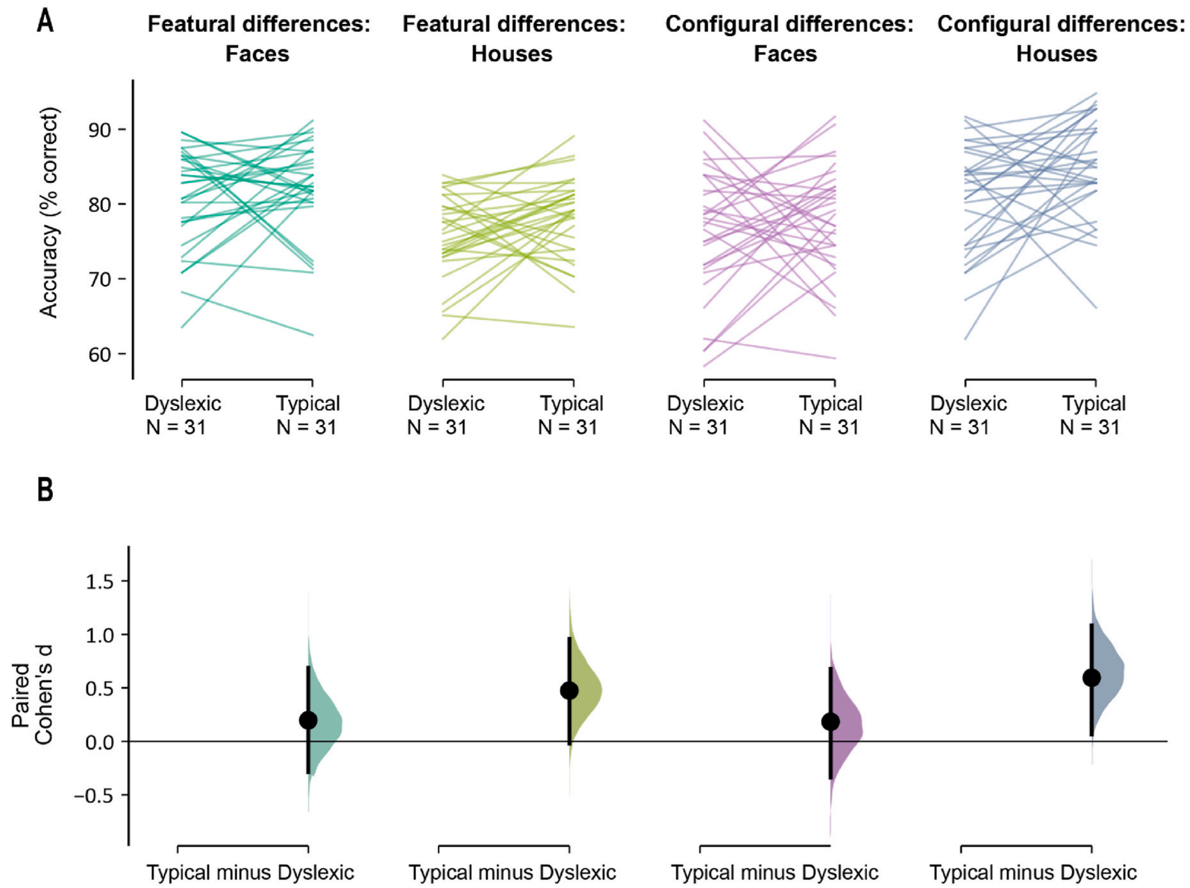


Fig. 4. Cumming estimation plot for paired D_{av} for featural and configural processing of faces and houses. A. The raw data is plotted for each paired set of observers connected by a line; B. Each paired mean difference is plotted as a bootstrap sampling distribution (5000 bootstrap samples were taken). Mean differences are depicted as dots; 95% confidence intervals are indicated by the ends of the vertical error bars, and they are bias-corrected and accelerated.

$SD = 6.48\%$; $t\ (30) = 0.50$, $p = .62$, $D_{av} = 0.11$, 95% CI [−2.27, 3.75]; configural faces: dyslexic readers $M = 76.33\%$, $SD = 8.63\%$; typical readers $M = 77.70\%$, $SD = 7.36\%$; t (30) = 0.78, $p = .44$, $D_{av} = 0.17$, 95% CI [−2.24, 5.00]; for group differences additionally broken up by difficulty levels, see Supplementary figure s1; for group differences after excluding participants with potential comorbidities, see Supplementary Information).

We performed a 2 × 2 x 2 repeated measures ANOVA (Table 2) with group (dyslexic and typical readers), stimulus (faces and houses) and process (featural and configural) as factors and accuracy as the dependent measure. The main effect of group was not significant according to a two-sided test ($p = .07$). No main effects of stimulus and process were found. The interaction of stimulus and process was significant ($p = <.001$) indicating that featural processing of houses was less accurate than featural processing of faces, while configural processing of houses was more accurate than configural processing of faces. There were no other significant interactions (between group and process, group and stimulus, or group, process, and stimulus).

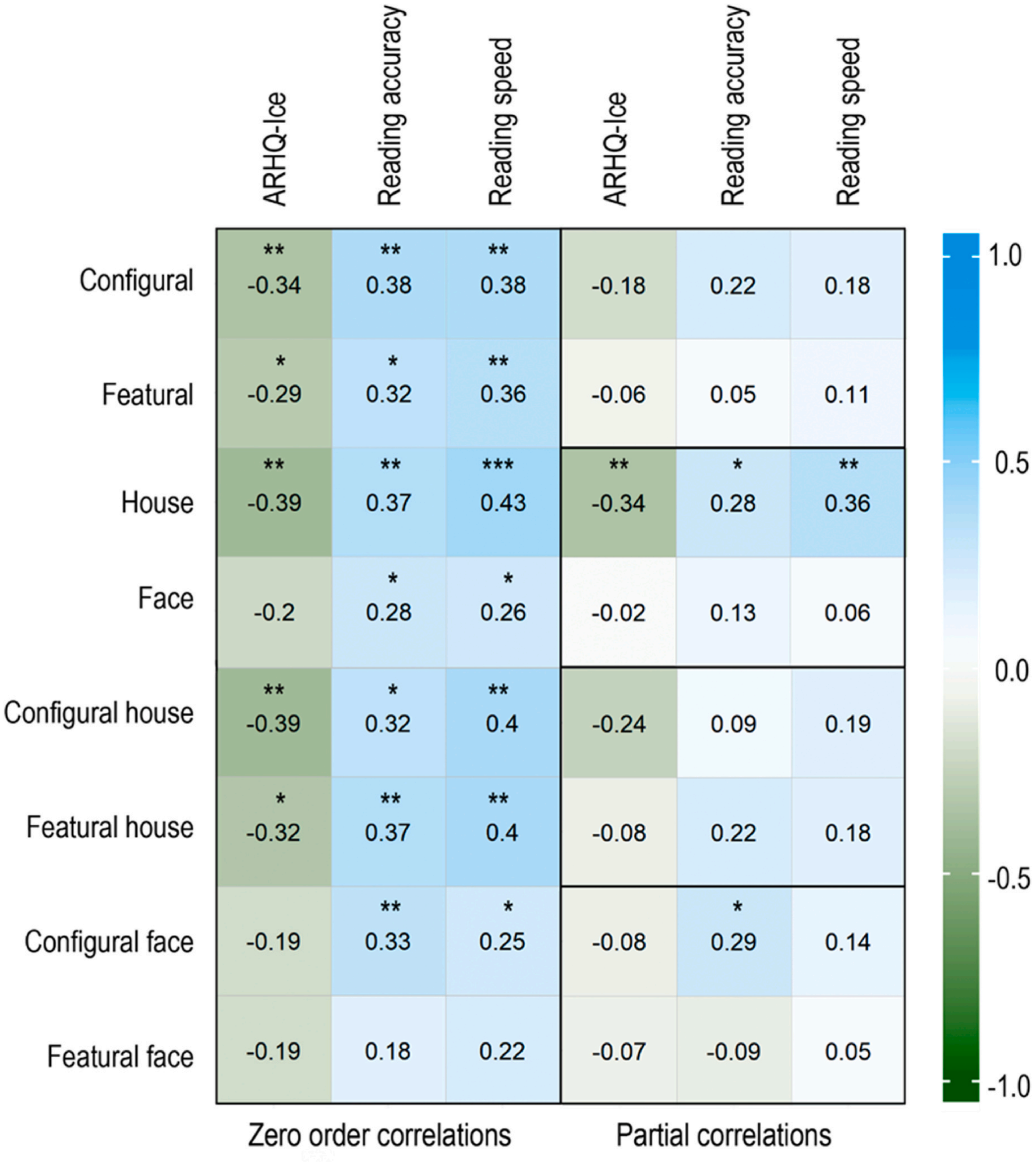
Table 2
Summary of 2 × 2 x 2 repeated measures ANOVA. $\widehat{\eta}_G^2$ indicates generalized eta-squared.

	F	p	$\widehat{\eta}_G^2$
Group	3.48	.07	.03
Stimulus	0.61	.44	.002
Process	0.64	.43	.001
Group × Stimulus	2.65	.11	.01
Group × Process	1.51	.23	.002
Stimulus × Process	164.20	<.001	.12
Group × Stimulus × Process	0.50	.49	<.001

The lack of main effects and interactions with group was surprising, although the non-significant main effect of group should be interpreted in the context that the test is conservative given that our hypothesis was clearly one-sided (i.e., dyslexic readers were predicted to do worse than typical readers). One possible reason is that visual recognition problems are modulated by educational level, as we have previously seen that group effects in visual recognition were solely driven by dyslexic readers without higher education (Sigurdardottir, Hjartarson, et al., 2019; their Fig. 3). This was supported by a significant three-way interaction between educational level, group, and stimulus, where the group difference was larger for houses compared to faces, but only for participants with lower educational levels. For further information, see "Repeated measures ANOVA with covariates" in the supplementary materials. We return to the group x process null result in the subchapter on representational similarity analysis (RSA).

3.6. Reading history problems, reading speed, and reading accuracy

We also assessed the association between performance on the visual tasks included in the object recognition task (accuracy for the four subtasks, as well as total accuracy for faces, houses, featural, and configural processing) and the three measures of reading performance (ARHQ-Ice, reading speed, reading accuracy). The results are summarized in Fig. 5. For additional analyses excluding participants with missing values for reading speed and accuracy for the IS-FORM/IS-PSEUDO reading tasks, and broken down by group membership, see Supplementary Information, Correlations of Object Recognition,



	Zero order correlations			Partial correlations		
	ARHQ-Ice	Reading accuracy	Reading speed	ARHQ-Ice	Reading accuracy	Reading speed
Configural	** -0.34	** 0.38	** 0.38	-0.18	0.22	0.18
Featural	* -0.29	* 0.32	** 0.36	-0.06	0.05	0.11
House	** -0.39	** 0.37	*** 0.43	** -0.34	* 0.28	** 0.36
Face	-0.2	* 0.28	* 0.26	-0.02	0.13	0.06
Configural house	** -0.39	* 0.32	** 0.4	-0.24	0.09	0.19
Featural house	* -0.32	** 0.37	** 0.4	-0.08	0.22	0.18
Configural face	-0.19	** 0.33	* 0.25	-0.08	* 0.29	0.14
Featural face	-0.19	0.18	0.22	-0.07	-0.09	0.05

Fig. 5. Correlations between reading measures and accuracy on the object recognition task. The three leftmost panels show zero order correlations (Pearson's *r*) and the three rightmost panels show partial correlation coefficients. Each box on the right-hand side indicates mutually partialled-out variables. The upper row of the topmost box shows correlations with configural processing accuracy when featural accuracy is partialled out, while the lower row of the same box shows correlations with featural processing accuracy when configural accuracy is partialled out. The upper row of the second box from the top shows correlations with house accuracy when face accuracy is partialled out, while the lower row of the same box shows correlations with face accuracy when house accuracy is partialled out. The upper row of the third box from the top shows correlations with configural house accuracy when featural house accuracy is partialled out, while the lower row of the same box shows correlations with featural house accuracy when configural house accuracy is partialled out. The upper row of the bottom box shows correlations with configural face accuracy when featural face accuracy is partialled out, while the lower row of the same box shows correlations with featural face accuracy when configural face accuracy is partialled out. Asterisks indicate significance levels: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Reading Speed And Reading Accuracy After Excluding Participants With Missing Reading Scores.

Featural face accuracy was not significantly correlated with any measures of reading performance, while configural face accuracy as well as total face accuracy were significantly associated with greater reading speed and accuracy. Featural house, configural house, and total house accuracy were significantly correlated with all measures of reading performance, where lower accuracy was associated with a greater history of reading problems, slower reading, and less accurate reading. Featural and configural processing (irrespective of stimulus type) were correlated with all measures of reading.

For a better understanding of the specificity of the relationship between performance on visual tasks and reading problems, we calculated partial correlation coefficients (Fig. 5). Total house accuracy was significantly correlated with all reading measures when total face accuracy was controlled for, showing that lower accuracy for houses was particularly related to reading difficulties. In addition, configural face accuracy was significantly correlated with reading accuracy when featural face accuracy was kept constant. Other partial correlations were not significant. For correlations of object recognition, reading speed, and reading accuracy divided by group, see Supplementary Information.

3.7. *Representational similarity analysis (RSA)*

While univariate methods are useful for comparing group averages, they cannot detect all informative data patterns. For example, how well featural performance predicts configural performance (and vice versa) can inform us on how differentiable these processes are. By relying solely on group averages, such relationships will be overlooked. In our case, dyslexic and typical readers could have comparable accuracy but the relations between conditions might still differ between the two groups. As an example, in general we would expect performance on featural trials to be more correlated with other featural trials than configural trials, and vice versa. However, this expected pattern might not be apparent in dyslexic readers if featural and configural trials are not actually differently processed. Representational similarity analysis (RSA), which originates in systems neuroscience, can provide a fuller description of the structure of information representation in each group. We use RSA to correlate individual responses within each group and evaluate the similarity of these correlation matrices (reference models) with predicted data patterns (conceptual models; Kriegeskorte et al., 2008).

To illustrate, assume that we have two conditions “A" and “B" (see Fig. 6). We will overlook the relationship between “A" and “B" if we just compare the total accuracy of “A" or “B" between two groups of dyslexic and typical readers. Two groups might be equally good at condition “A" or “B" but employ different strategies to achieve that. If “A" and “B" tap into different skills or require different strategies, the accuracy of a trial with task “A" should be more correlated with the accuracy of another trial of task “A" than a trial with task “B". In this case, the left pattern of Fig. 6 will be our conceptual model that assumes “A" and “B" are independent skills or require different strategies. “If “A" and “B" are not independent but instead tap into the same skills, then a trial from “A" should be no more correlated with another trial with “A" than it is with a trial with “B", and we would see the right pattern in Fig. 6. RSA measures how well such patterns or conceptual models correspond to the real data.

In the first step of the RSA, we developed our reference models, one for dyslexic readers and another for typical readers. The reference models are correlation matrices of the accuracy of featural and configural processing of faces and houses with the four different difficulty levels (Fig. 7, panel A). We calculated the mean accuracy for each participant on all 16 combinations of trial types, including two different stimulus types (faces or houses), two different process types (featural or configural), and four different difficulty levels (0, 1, 2, 3). Each reference model cell represents the correlation across participants of two trial types, such as the correlation between people’s accuracy for featural faces with the difficulty level of 1 and their accuracy with configural houses with the difficulty level of 2.

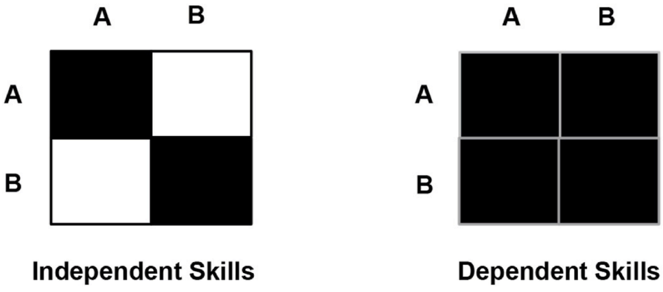


Fig. 6. Illustrative conceptual models. Darker colors indicate higher correlation.

We then created three conceptual models based on possible predicted patterns for stimuli, processes, and difficulty levels. For the stimulus matrix, the values of the conceptual model were “1″ when the stimuli on the compared trial types came from the same category (both faces or both houses) but were otherwise set to “0" (one face and the other house). A similar pattern would be found in a reference model if people’s performance on a stimulus category was better predicted by their performance on other trials from that category than trials from a different category. The process matrix, the second conceptual model, followed the same logic, but for processes (featural versus configural): the provided values were “1″ when the processes matched (both featural or both configural), but “0″ otherwise (one featural and the other configural). A reference model would be expected to follow this pattern if the putative processes were separable, so a person’s performance with one type of process would better predict another trial where that same process was used, as opposed to a trial with the other process. A scale (1, 0.75, 0.25, 0) was used for the conceptual model of difficulty levels, the difficulty level matrix, where greater numbers indicated greater similarity in difficulty; “1″ therefore stood for identical difficulty levels and “0″ stood for the most different levels (Fig. 7, panel B). It should be noted that we did not necessarily expect to see this pattern in the reference models, as it would require performance on trials of a specific difficulty level to best predict performance at that same difficulty level. Different difficulty levels might however not depend on distinct mechanisms; if a participant performs well on easy trials compared to others, then he or she might also perform comparatively well on more demanding trials. This conceptual model was therefore included mainly for the sake of completeness.

To reduce the possibility of spuriously low p-values, each model’s diagonal (which has correlational coefficients of 1 by definition) and one off-diagonal triangle (a mirror version of the other off-diagonal triangle) was omitted and then converted into a vector before comparing reference models with the three conceptual models (stimuli, processes, and difficulty levels). Two multiple regression analyses were performed, one with the typical reader reference vector and another one with the dyslexic reader reference vector as dependent variables. The three conceptual vectors were used as independent variables to estimate to what degree stimuli, processes, and difficulty levels contributed to the reference vectors for dyslexic and typical readers.

As summarized in Table 3, a significant regression equation was found for typical readers ($p < .001$). Both stimulus ($t\,(116) = 8.13$, $p < .001$) and process ($t\,(116) = 4.40$, $p < .001$), but not difficulty levels ($t\,(116) = 0.86$, $p = .39$), significantly predicted the typical reader reference model. The regression equation was also significant for dyslexic readers ($p < .001$), but the only significant independent predictor for the dyslexic reader reference model was stimulus ($t\,(116) = 9.29$, $p < .001$), while process ($t\,(116) = 0.65$, $p = .52$) and difficulty levels ($t\,(116) = 1.32$, $p = .19$) were not significant. Stimulus type (face vs. house) dominated the patterns of both typical and dyslexic readers and both groups performed differently for different stimulus classes, but how well the data pattern represented processes (featural vs. configural) varied considerably between the two groups. Performance was more consistent for typical readers when process was constant. Dyslexic readers did not perform differently when processes were expected to differ, and seemingly relied on a single process that was indistinguishable for supposed featural and configural trials. Group differences in the separability of processes could not be attributed to disorders other than dyslexia (see Supplementary Information, Representational Similarity Analysis (RSA): Group Differences in The Separability Of Processes After Excluding Participants With Other Disorders).

We redid the RSA separately for faces and houses to explore whether process differences between dyslexic and typical readers could be identified for both stimulus categories. Process was not a significant predictor of the reference model for dyslexic readers, and this was true

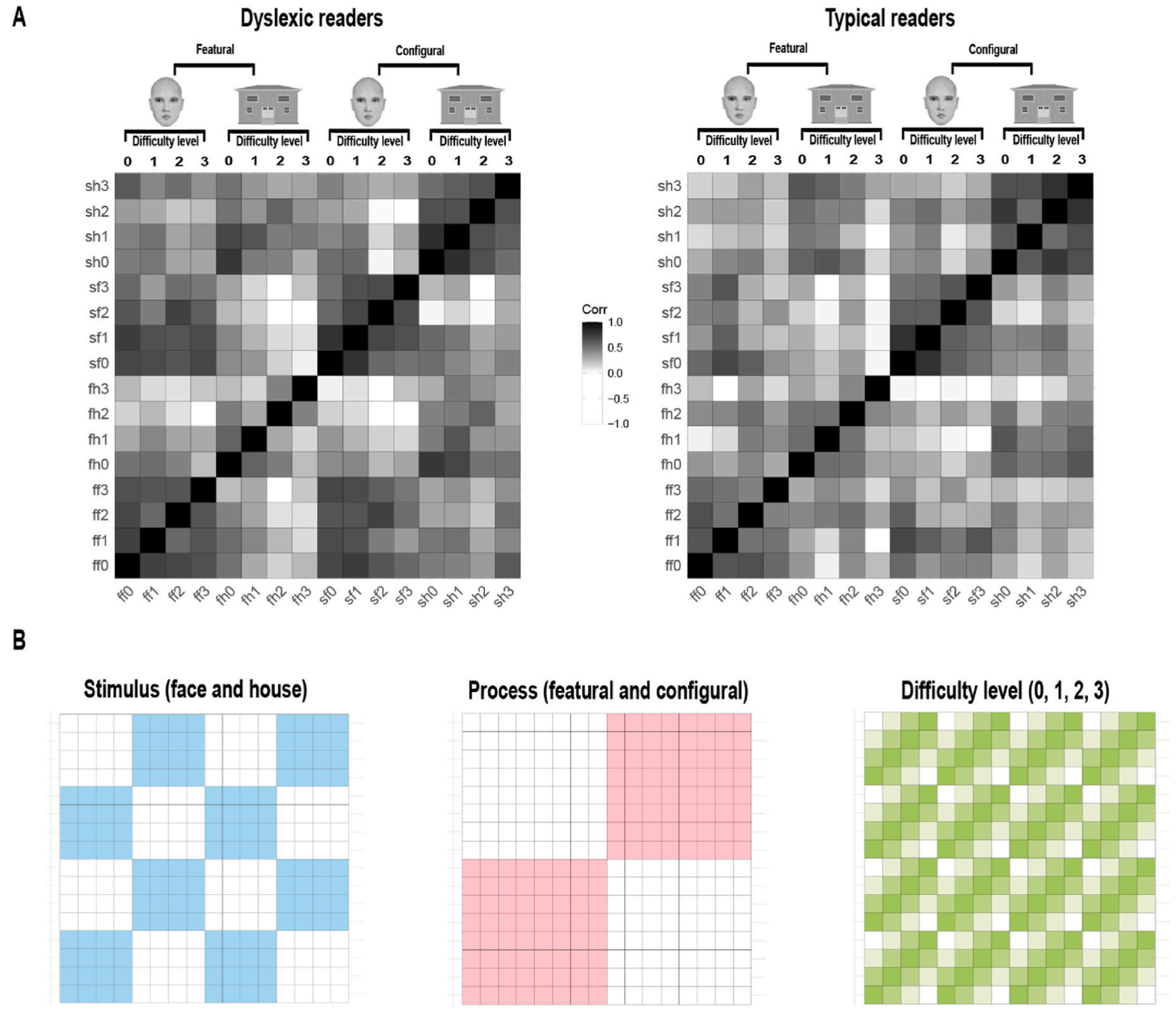


Fig. 7. A. Reference models for Representational Similarity Analysis (RSA): Correlation matrices of dyslexic and typical readers; B. Conceptual models. Left: Stimulus matrix; Middle: Process matrix; Right: Difficulty level matrix. Abbreviations: Corr: correlation (Pearson's r); ff: featural faces; fh: featural houses; sf: second-order configural faces; sh: second-order configural houses; 0–3: difficulty levels.

Table 3

Summary of representational similarity analyses (RSA). Multiple regressions with dyslexia or typical vectors as dependent variables, and stimulus, process and difficulty level as predictors.

Predictor	Dyslexic				Typical			
	b	95% CI	t (116)	**P**	**b**	95% CI	t (116)	**p**
Intercept	0.23	[0.16, 0.31]	6.27	<.001	0.17	[0.11, 0.24]	5.05	<.001
Stimulus	0.28	[0.22, 0.34]	9.29	<.001	0.23	[0.17, 0.28]	8.13	<.001
Process	0.02	[-0.04, 0.08]	0.65	.52	0.12	[0.07, 0.18]	4.40	<.001
Difficulty level	0.06	[-0.03, 0.14]	1.32	.19	0.03	[-0.05, 0.11]	0.86	.39

for both faces ($b = 0.05$, $t\,(25) = 1.41$, $p = .17$) and houses ($b = 0.05$, $t\,(25) = 0.85$, $p = .40$). Importantly, for typical readers, process for faces was a significant predictor ($b = 0.15$, $t\,(25) = 2.87$, $p = .01$), and process for houses was close to significance ($b = 0.14$, $t\,(25) = 1.96$, $p = .06$). Therefore, dyslexic readers apparently rely on only one process, and do not distinguish between supposedly featural vs. configural faces, or featural vs. configural houses.

As the results of Sigurdardottir, Hjartarson, et al. (2019) and our univariate analyses (see Supplementary Information, Repeated measures ANOVA with covariates) showed that the visual problems of dyslexic readers were modulated by educational level, we investigated whether group differences in the separability of processes were also restricted to lower educational levels and found out that it was not. For this, we developed a novel method for doing individual statistics on RSA analyses. For details, see Supplementary Information, Representational Similarity Analysis (RSA): Possible Modulation by Educational Level.

To assess the likelihood that the difference in process between the groups was due to chance, we performed a two-sided permutation test where the group labels (dyslexic and typical readers) were randomized. Next, RSA was calculated based on the permuted labels, i.e. two randomized ("fake") groups were created, and their reference models were calculated. We then computed the difference between the unstandardized *b*s of process, stimulus, and difficulty level for the randomized groups, repeating these steps 10,000 times and comparing the distribution of these random group differences to the *b* differences for the original unpermuted RSA. There was no significant difference between permuted and unpermuted RSAs for stimulus ($p = .72$) and difficulty level ($p = .79$), but the difference for process was significant ($p = .02$) suggesting that the observed process difference in dyslexic and typical readers is real.

4. Discussion

Our first major goal was to examine whether dyslexic readers have problems with recognizing non-word visual objects, and whether any such deficits are domain-specific, restricted to the processing of written words, or domain-general, affecting the recognition of other visual stimuli, such as faces and houses. Visual problems in dyslexia generalized to other visual domains, and seemingly more to some visual categories than others, as our participants with dyslexia had difficulty with house recognition but not face recognition. Furthermore, lower accuracy for houses was related to reading difficulties even when accuracy for faces was kept constant. A second major goal was to investigate whether visual problems in dyslexia are specific to either featural or configural processing. Initially, problems in dyslexic readers did not seem to be process specific as there was no detectable group difference in mean accuracy for featural vs. configural processing. But representational similarity analyses (RSA) revealed differences in the recognition processes used by dyslexic and typical readers that were not detected by traditional univariate analyses. Featural and configural processes were clearly separable in typical readers, while dyslexic readers appeared to rely on a single process to identify visual objects. This effect for processes was general, not restricted to either faces or houses.

How can our findings be integrated with previous studies that have produced contradictory results? As in the current study, Sigurdardottir et al. (2015) found problems in non-face object recognition of dyslexic readers and in Brachacki et al. (1995) dyslexic readers recognized traffic signs less accurately than typical readers. Huestegge et al. (2014) showed that dyslexic readers have problems in representing highly detailed visual objects in long-term memory. Conversely, Gabay et al. (2017) and Sigurdardottir et al. (2018) failed to find problems with object perception in dyslexic readers. This discrepancy could be rooted in methodological differences. The tasks were perceptual in Gabay et al. (2017) where participants estimated whether two simultaneously presented pictures of cars were identical. Similarly, participants in Sigurdardottir et al. (2018) matched simultaneously presented novel objects ("YUFOs") with which observers had no visual experience. Conversely, the current tasks and in Sigurdardottir et al. (2015) involved a memory component where participants had to indicate which objects they had seen previously. In our current study, we nonetheless found intact memory for faces so dyslexic readers are not likely to have a general problem with poor memory. Additionally, Sigurdardottir et al. (2015) assessed color memory which appeared to be intact in dyslexic readers, and visual problems of dyslexic readers in Sigurdardottir, Hjartarson, et al. (2019) were not connected to verbal working memory problems.

Another factor that might explain the apparent contradictions is education level. Dyslexic readers with lower educational levels are likely to have more severe dyslexia. The difference in house recognition accuracy between dyslexic and typical readers was largely driven by those with lower educational levels, while dyslexic readers with higher educational levels displayed performance comparable to matched typical readers. Earlier research has also suggested that visual recognition problems of dyslexic readers differ by education levels (Sigurdardottir, Hjartarson, et al., 2019), although here we found this for house recognition while the earlier study reported this for face recognition. This may explain why Gabay et al. (2017) did not find a problem with non-face object recognition, since their participants were university students.

Nevertheless, while dyslexic readers' problems were not restricted to recognizing words, they had no detectable difficulty with face recognition, and dyslexia in this study was only associated with non-face object recognition problems. This is compatible with the claim that domain-specific processes are involved in face processing (e.g. Yovel and Kanwisher, 2004), and that recognition of faces and words can be selectively affected by brain injury or developmental disorders (Robotham and Starrfelt, 2017). Intact face recognition in dyslexia stands in contrast to accounts suggesting a mutual dependency between words and faces (Behrmann and Plaut, 2019; Dehaene et al., 2010; Plaut and Behrmann, 2011). Our result is also somewhat at odds with results from the Back of the Brain project (Rice et al., 2020) where the authors claim that the general organizational principle for patients with posterior cerebral artery stroke was that of associations between word and face processing; a minority of patients did nonetheless show disproportionate deficits for word recognition. We should note that according to some accounts (Bishop, 1997; D'Souza and Karmiloff-Smith, 2011), findings of developmental deficits (e.g., dyslexia) are not necessarily related to normal cognition, as they postulate that brains of people with developmental deficits develop differently.

Recognizing faces and words is generally done daily, while recognizing houses is arguably a task in which people engage less frequently. The lack of a face recognition problem in our univariate analysis is not consistent with a visual expertise problem in dyslexia (Lieder et al., 2019; Sigurdardottir et al., 2017, 2018). Such a problem is expected to manifest as greater recognition difficulties for visual categories with which people have the most experience, such as faces and words. We nonetheless should not claim based on these data alone that visual recognition problems in dyslexic readers are completely unrelated to experience; houses are, after all, familiar objects. Neither should we make strong claims that people with dyslexia have problems with all non-face object recognition as houses might not be representative of all object categories. According to Richler et al. (2017), the assumption that non-face object processing has a common mechanism that varies little from one non-face category to another can be questioned. Several studies have reported dissociations for brain areas involved in recognizing animals vs. tools (e.g., Chao et al., 2002), large vs. small objects (e.g., Konkle and Oliva, 2012) or curvilinear vs. rectilinear objects (e.g., Nasr et al., 2014; Yue et al., 2014). Also, according to recent research, the mean pairwise correlation ($r = 0.33–0.34$) in performance across object recognition tests (e.g., butterflies, cars, planes, shoes, dinosaurs; McGugin et al., 2012; Van Gulick et al., 2016) was no higher than the usual correlation between face and non-face object recognition tests (e.g., $r = 0.37$ in Dennett et al., 2012). We chose our stimuli as they are well-controlled and span a wide range of difficulty levels (Collins et al., 2012) which can therefore capture a wide range of individual differences. To generalize our results, it might nonetheless be beneficial to include more visual categories in future investigations and manipulate featural and configural information in words.

Several studies have found impairments in face processing of dyslexic readers (Collins et al., 2017; Gabay et al., 2017; Sigurdardottir et al., 2018; Sigurdardottir, Hjartarson, et al., 2019; Sigurdardottir et al., 2015) while others have not (Brachacki et al., 1994; Holmes and McKeever, 1979; Rüsseler et al., 2003; Smith-Spark and Moore, 2009). We should note that configural face processing accuracy was positively correlated with reading accuracy when featural face processing accuracy was kept constant, although it was not associated with dyslexia (see partial correlations in Fig. 6). This is seemingly inconsistent with Ventura et al. (2013) who showed that in comparison to illiterates, literates process faces less holistically, but more consistent with Cao et al. (2019) who showed that illiterates were less sensitive to changes in the configural processing of faces and houses and concluded that later experience in reading can reshape configural processing. Cao et al. (2019) argued that the paradigm might be a key factor to explain the apparent discrepancies between these results, as they measured second-order configural processing, but Ventura et al. (2013) used the complete composite face paradigm, which represents the failure of selective attention. Therefore, inadequate experience with reading could possibly lead to both reduced reading accuracy and limited ability for second-order configural face processing.

As reviewed by Ventura (2014), visual word representations of expert readers may overtake cortical space that otherwise would have been dedicated to face processing. Reading acquisition could therefore trigger right hemispheric lateralization for faces, and additionally have detrimental effects on face processing abilities as suggested by Dehaene et al. (2010). Our data show that the accuracy of configural face processing is positively correlated with reading performance. This is more in alignment with the possibility that literacy enhances representational similarity between text and faces and reorganizes cortical function without inducing direct cortical competition with other visual categories (Hervais-Adelman et al., 2019).

One possible reason for conflicting results on visual processing in dyslexia is that some tasks involve a visual processing mechanism deficient in dyslexia, while dyslexic readers can in other cases rely on a separate intact visual mechanism. However, in the current study, the problem with houses was found for both featural and configural manipulations, and we found neither featural nor configural processing difficulties for face recognition in the univariate analysis of accuracy. This may suggest that dyslexia is not process specific and is, at a first glance, inconsistent with studies showing a featural processing deficiency (Sigurdardottir, Arnardottir, et al., 2019) in dyslexic readers. But there are several alternative explanations for this result. According to Rakover (2002), configural changes such as those used in the current study may inadvertently involve featural changes, and vice versa. For example, manipulating the space between the eyes can be interpreted as a featural change in the nasal bridge. Furthermore, we modified second-order relations, one type of configural information, but other types of configural processing may be unrelated to it (Maurer et al., 2002). Rezlescu et al. (2017) argue against the use of a single term for configural processing, because different tasks reflect distinct perceptual mechanisms. The same may even be true for featural processing. For example, Sigurdardottir, Arnardottir, et al. (2019) used a different way of manipulating featural vs. configural processing; while we changed the distances between features for configural processing, they manipulated the form of the skull, muscles, and fat structure. For featural manipulation, internal features from one face were transferred to another face with a different global form (for details, see Van Belle et al., 2009). These different manipulations might lead to similar results, but the processes for performing these tasks may differ. Similar to the different manipulations that supposedly all measure “configural processing“, different featural manipulations might not assess the same underlying mechanisms. Further research is required to investigate similarities and differences in these methods. But to summarize, the use of particular stimulus manipulations does not guarantee “featural” and “configural” processing.

Differences in task demands may also contribute to literature inconsistencies. For example, in our face task the sample and the match were identical images, and participants were required to hold the sample face in memory for 300 ms (visual short-term or working memory), while previous studies reporting group differences in face processing used visual tasks that were based on long-term memory and/or non-identical samples and matches (e.g. Gabay et al., 2017; Sigurdardottir et al., 2019a,b; Sigurdardottir et al., 2018; Sigurdardottir et al., 2015). Even though we included size differences between sample and choice images specifically to discourage low-level strategies, the current task may still have enabled template matching or other methods that do not tax invariant high-level visual processes. Left hemisphere regions hypoactive in dyslexic readers (Richlan et al., 2011) might be particularly relevant for invariant object recognition – hypothesized to involve a feature- or part-based strategy – so weaknesses in such a system are likely less noticeable when a task can be solved with a holistic processing strategy, by matching to specific exemplars (Marsolek, 1999; but see Curby et al., 2004).

Also, as in our task participants were first presented with a sample that was either a face or a house, they were aware that the task would involve a particular object category, but the optimal processing strategy – featural vs. configural – was unknown until the match and foil appeared. Participants could therefore have changed strategy primarily based on stimulus category and not process. This could be why the process conceptual model pattern is not very apparent even for typical readers, as depicted in Fig. 7. While the univariate analysis did not reveal process differences, it was still clear from the more sensitive RSA analysis that the typical readers indeed solved the featural and configural tasks using different strategies, while the dyslexic readers did not.

Importantly, univariate analyses of accuracy miss that two people with equivalent performance can solve a task using different strategies. Even though no overall group differences were found for featural vs. configural accuracy, this does not mean that the tasks were solved using similar representations or the same underlying mechanisms. Our RSA analyses revealed differences in the visual recognition processes used by the two groups. To clarify, if two different processes (one featural and another configural) or stimuli (one face and another one house) were in fact supported by separable mechanisms, we expected performance for one type of process or stimulus to better predict a trial with an equivalent process or stimulus than a trial with a different process or stimulus. The RSA results showed that typical readers performed differently depending on both stimulus category (faces vs. houses) and processing type (featural vs. configural), while dyslexic readers performed differently based on stimulus category, but not process. The RSA also showed that process differences between dyslexic and typical readers are not restricted to only one stimulus category as the pattern was observed for both faces and houses.

These group differences in process might be experience-dependent. If dyslexic readers have problems with acquiring expertise (Brachacki et al., 1995; Lieder et al., 2019; Sigurdardottir et al., 2017), then the underlying processing mechanisms could differ from typical readers with acquired expertise, as experience with a stimulus category can affect how it is processed (Bukach et al., 2006; Gauthier and Bukach, 2007; Gauthier and Tarr, 2002; Hsiao and Cottrell, 2009; Zhang et al., 2005). Cao et al. (2019) also suggest that literacy acquisition can reshape configural processing in general. The lack of a process by education interaction in our RSA results however makes it less likely that processing differences between dyslexic and typical readers are related to differences in reading experience as dyslexic readers with different educational backgrounds likely have considerably different reading experience. Another possibility is that some cases of dyslexia are a product of fewer available intact visual processes, as flexibly switching between different processes can be important for recognizing objects. Exactly pinning down these visual processes is a topic worthy of further study.

Developmental dyslexia is not the only developmental disorder where featural or configural processing could differ. For example, a meta-analysis revealed that people with autism are slower at global or configural perception than controls (Van der Hallen et al., 2015). Another study suggested that children with autism prefer to report the local properties of a stimulus (Koldewyn et al., 2013). When asked to report the global properties, their performance was comparable to that of the control group, indicating that they have a disinclination in using global processing rather than a disability. Kalanthroff et al. (2013) reported no differences in interference between irrelevant global stimuli and irrelevant local stimuli, implying that there is no global-to-local interference in adults with ADHD. Song and Hakoda (2012, 2015) argued that people with ADHD have local-to-global interference rather than global-to-local interference. As indicated in the supplementary material, omitting people with autism or ADHD, as well as their matched participants, had only a minor impact on our Representational Similarity Analysis (RSA); therefore, they are not the primary reason for the inseparability of featural and configural processing in dyslexia found here. There is evidence that face recognition deficits in developmental prosopagnosia might be linked to a weakness in holistic processing of faces (Avidan et al., 2011; DeGutis et al., 2014; Palermo et al., 2011; Towler et al., 2018). In future studies we aim to perform RSA on featural and configural processing in people with developmental prosopagnosia and compare them with dyslexic readers, especially given that RSA can uncover differences that might otherwise go undetected in more traditional univariate analyses. More generally, our RSA results show that relying solely on mean accuracy to look for group differences can be deceptive as group means could be equal while data patterns could differ, hinting at different representations and different underlying mechanisms. Therefore, RSA implementations can be used effectively to explore variations in the visual representations of dyslexic and typical readers as well as other comparisons of group differences, such as other developmental disorders.

5. Conclusions

We draw two main conclusions here. Firstly, our results suggest that some dyslexic readers show object recognition impairments. This argues that problems in dyslexia are not restricted to reading which suggests that dyslexia– and visual word processing more generally – is not domain-specific. Such visual processing deficits cannot easily be attributed to phonological problems, consistent with the idea that dyslexia is a heterogeneous disorder. One alternative could be a high-level visual deficit in some dyslexic readers which could manifest as difficulties in reading. The direction of causality nonetheless needs further study.

Secondly, our RSA results suggest that dyslexic readers rely on a single process to identify visual objects. This demonstrates the effectiveness of representational similarity analysis (RSA) in behavioral studies. While univariate analyses failed to uncover process differences between dyslexic and typical readers, RSA revealed that dyslexic readers depend on only a single visual process regardless of whether features or configurations are task-relevant. This process effect was general, occurring for both faces and houses. Our results suggest that dyslexic readers' general failure to use different processes may be responsible for their reading problems and that for efficient reading, both featural and configural processing are required.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2021.108059.

Credit author statement

Bahareh Jozranjbar: Data collecting, Data analyzing, Visualization, Writing- Original draft preparation, Writing- Reviewing and Editing. **Árni Kristjánsson**: Supervision, Resources, Funding acquisition, Writing- Reviewing and Editing. **Heida Maria Sigurdardottir**: Supervision, Conceptualization, Methodology, Resources, Funding acquisition, Project administration, Writing- Reviewingand Editing.

Open practices statement

A preprint of this paper is available at https://psyarxiv.com/u6vqb. Data can be made available to other researchers upon request provided that the National Bioethics Committee of Iceland grants them permission for such access and provided that such access adheres to all Icelandic laws regarding data privacy and protection.

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