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Atypical perceptual processing of faces in developmental dyslexia

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ABSTRACT

Developmental Dyslexia (DD) is often attributed to phonological processing deficits. Recent evidence, however, indicates the need for a more general explanatory framework to account for DD's range of deficits. The current study examined the specificity versus domain generality of DD by comparing the recognition and discrimination of three visual categories (faces and words with cars as control stimuli) in typical and dyslexic readers. Relative to controls, not only did dyslexic individuals perform more poorly on word recognition, but they also matched faces more slowly, especially when the faces differed in viewpoint, and discriminated between similar faces (but not cars) more poorly. Additionally, dyslexics showed reduced hemispheric lateralization for words and faces. These results reveal that DD affects both word and face, but not car, processing, implicating a partial domain general basis of DD. We offer a theoretical proposal to account for the multifaceted findings and suggestions for further, longitudinal studies.

1. Introduction

Developmental dyslexia (DD), also known as 'specific reading disability', is a disorder in which children with normal intelligence and sensory abilities show substantial deficits in reading. Although most research on DD has been conducted with children or adolescents, the reading difficulties can persist across the lifespan (Shrewsbury, 2016) and can adversely affect the work participation of such individuals (de Beer, Engels, Heerkens, & van der Klink, 2014).

Despite decades of research, the underlying psychological bases of DD continue to be debated (for reviews see, Démonet, Taylor, & Chaix, 2004; Habib & Giraud, 2012). The commonly held view is that DD arises from deficient phonological representations and, indeed, phonological impairments are among the most common symptoms associated with DD (Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, DD is also related to deficits in orthographic processing (Badian, 2005; Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013; Pugh et al., 2000), visual and auditory processing (Clark et al., 2014; Farmer & Klein, 1995), attention (Facoetti et al., 2006) and procedural learning (Nicolson & Fawcett, 2007) and intervention along a host of different domains can result in improvement in DD (Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2014; Heim, Pape-Neumann, van Ermingen-Marbach, Brinkhaus, & Grande, 2014). The multi-faceted nature of DD has led researchers to search for a general explanation to account for the diversity of deficits, although there remains no clear consensus on this topic (Hari & Kiesilä, 1996; Nicolson & Fawcett, 2011; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010).

Just as with the cognitive profile, there is also substantial controversy regarding the underlying neural abnormalities associated with DD. For example, many recent studies have uncovered a variety of signatures of the disorder (compared with typical readers), including reduced BOLD signal in left extrastriate cortex (Langer, Benjamin, Minas, & Gaab, 2013; Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Pugh et al., 2000; Wandell, Rauschecker, & Yeatman, 2011), lower amplitude magnetoencephalography signals in the vicinity of the left inferior occipitotemporal cortex (Salmelin, Service, Kiesila, Uutela, & Salonen, 1996), as well as changes in gray-white matter proportion and in the integrity of white matter tracts in these same regions (see Richlan, Kronbichler, & Wimmer, 2012; Wandell et al., 2011). Others have argued that alterations in temporo-parietal cortex constitute the neural basis of DD (Raschle, Zuk, & Gaab, 2012), although these alterations are often observed in conjunction with changes in occipitotemporal cortex.

The differences in left ventral occipitotemporal (VOT) cortex in DD, relative to controls, are consistent with a deficit in visual processing in some, if not all, individuals with DD. A key question is whether this visual recognition deficit is restricted to written words i.e., is domain specific or, alternatively, extends to the processing of other classes of visual stimuli (for a review see, Schulte-Körne & Bruder, 2010) and is more domain general. This

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controversy bears on more general arguments about domain-specificity within the visual system, particularly with regard to the visual word form area (Dehaene & Cohen, 2011; Dehaene, Cohen, Morais, & Kolinsky, 2015; Price & Devlin, 2011; Roberts et al., 2012; Vogel, Petersen, & Schlaggar, 2014). A highly informative contrast, and the focus of this paper, concerns the nature of the visual abilities of adults with DD and whether their recognition impairment extends beyond words to another specific category of stimuli, namely faces.

1.1. Interdependence of word and face processing

Words and faces constitute an interesting matched pair because, even though they are entirely unrelated in terms of image statistics, they both require distinguishing a large number of homogeneous exemplars and the perceptual expertise of literate individuals is greatest for these two classes of visual stimuli. Much evidence has suggested that words and faces are recognized by independent mechanisms: words by the Visual Word Form Area (VWFA) in VOT in the left hemisphere (LH) (Petersen, Fox, Posner, Mintun, & Raichle, 1988), and faces by the Fusiform Face Area (FFA) in an approximately homologous region in the right hemisphere (RH) (Kanwisher, McDermott, & Chun, 1997), although this strictly binary account has not been as strongly endorsed recently (Dehaene et al., 2015).

Consistently, a recent theoretical proposal (Behrmann & Plaut, 2013; Plaut & Behrmann, 2011) postulates that, because of specific constraints on neural and cognitive development, these domains are interdependent, both structurally and functionally (for related ideas, see Dehaene & Cohen, 2007; Dehaene et al., 2010). According to this proposal, due to within-category exemplar homogeneity, both words and faces place extensive demands on high-acuity vision. As a consequence, words and faces compete for representational space in both hemispheres in the region of extrastriate cortex adjacent to higher-level retinotopic cortex that encodes central visual information (Levy, Hasson, Avidan, Hendler, & Malach, 2001), notably including both the VWFA and FFA. Additionally, in order to minimize connection length and overall axon volume, word representations are further pressured to be more proximal to language/phonological processing, which is left-lateralized in most individuals, and so the LH visual area is increasingly tuned for the representation of orthographic inputs. Because the image statistics of words and faces differ so greatly, the two types of stimuli cannot be fully co-localized and so, by virtue of competition from word representations in the LH, face representations gradually, although not exclusively, become more right-lateralized. As a result of these cooperative and competitive dynamics over the course of development, in the typical mature state, words are more strongly represented in the LH and faces are more strongly represented in the RH. However, both domains are processed bilaterally, such that the efficacy and degree of hemispheric lateralization of the two domains is causally linked and subject to a variety of factors that vary across individuals. In light of this theoretical proposal, one might predict an impairment in DD for both word and face processing.

1.2. Face processing in developmental dyslexia

In contrast with the view above, domain specific accounts of DD predict that face processing should be normal in DD. Although the existing literature on face processing in DD is not extensive, at first glance it might appear to support these accounts. For example, Brachacki, Fawcett, and Nicolson (1994) reported no difference between DD and non-DD individuals in face recognition. Similarly, Smith-Spark and Moore (2009) found that DD and non-DD university students did not differ in the speed or accuracy with which faces were named, although the non-DD group was significantly faster to name early- than late-acquired faces of famous individuals. Also, several studies have demonstrated that DD individuals were unimpaired in recognition memory for unfamiliar faces (Rüsseler, Johannes, & Münte, 2003) and performed normally when ordering unfamiliar faces in an old/new sequence (Holmes & McKeever, 1979).

Closer examination, however, suggests that the existing results are less than definitive. First, some studies may have been insensitive to group differences because performance was at ceiling (e.g., Brachacki et al., 1994), consistence with findings demonstrating that DD participants perform similarly to typical readers in simple tasks, and group differences emerge only when task difficulty is increased (dual task, inserting noise, or increasing perceptual demands) (Fawcett & Nicolson, 1992; Gabay, Schiff, & Vakil, 2012; Sperling, Lu, Manis, & Seidenberg, 2005; Yap & van der Leij, 1994; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Second, previous studies focused more on the mnemonic than perceptual aspects of face perception, showing no group differences in recognition memory and/or naming when participants were able to encode the faces well (large size faces, long exposure duration etc.) (Brachacki et al., 1994; Rüsseler et al., 2003; Smith-Spark & Moore, 2009). One recent study that examined the perceptual, rather than mnemonic, performance of DD individuals found that they were not only impaired at face perception but were also impaired at perceiving other visually complex stimuli, especially when within-class stimuli need to be differentiated (Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). Given the ambiguity of the existing empirical findings, the current study aimed to assess the integrity of face processing skills in DD adults to determine whether, and to what extent, face perception and its lateralization is adversely affected in this population. Such findings will help adjudicate between a domain-specific versus more domain-general account of the disorder.

In the current work, we test the face perception performance of DD individuals in a number of investigations, each of which is designed to elucidate, in detail, the extent and nature of any observed impairment. For example, in addition to quantifying performance during matching of upright faces, we compare the performance of the DDs and controls for upright and inverted faces to determine whether the DD individuals exhibit the standard decrement when faces are misoriented, the so-called ‘face inversion’ effect (Bruce, Valentine, & Baddeley, 1987). We also explore the effect of viewpoint, or depth rotation to assess whether the DDs show the expected cost in matching faces shown across different viewpoints. Last, we examine the integrity of face perception under conditions when faces are parametrically morphed to be increasingly perceptually alike, thus allowing us to carefully characterize performance as a function of task difficulty. Together, these manipulations provide sensitive measures of the strengths and weaknesses of face perception in DD. We also examine the DD’s performance on a control stimulus set, cars, to determine whether any deficits observed for faces might be a result of a general visual processing impairment that affects many visual classes and not just words and faces. Finally, motivated by the interdependent hemispheric account (see above), using a divided field paradigm, we compare the hemispheric lateralization effects for cars, words and faces in DD and control participants.

2. Experiment 1: Face matching across inversion and viewpoint

2.1. Participants

Thirty participants, 15 with DD (9M, 6F) and 15 matched controls (9M, 6F) participated in this experiment. Of the participants, 24 were native English speakers (12 DD and 12 controls) and six were native Hebrew speakers (three DD and three controls).

English readers. The 24 native English speakers were university students in Pittsburgh, from families with middle to high socioeconomic status. No individual had sensory or neurological deficits or attention deficit hyperactive disorder (according to the American Psychiatric Association, 2000). A well-documented history of dyslexia constituted the key inclusion criterion for the DD group: (1) each individual received a formal diagnosis of DD by a qualified psychologist prior to inclusion in this study; (2) each individual's diagnosis was verified by the diagnostic and therapeutic center at their university and they were receiving accommodations appropriate to their educational setting. The control group comprised individuals, age-matched with the DD participants, with no reported reading difficulty. The study was approved by the Institutional Review Board of Carnegie Mellon University, and written informed consent was obtained from all participants.

Participants completed a series of tests including verbal working memory (as measured by the forward and backward Digit Span from the Wechsler Adult Intelligence Scale, (Wechsler, 1997)), rapid naming (Wolf & Denckla, 2005) and phonological awareness (Spoonersim test adapted from Brunswick, McCrory, Price, Frith, & Frith, 1999). The Raven- Matrices test was used as a proxy of non-verbal intelligence (Raven, Court, & Raven, 1992) so as to avoid the verbal demands of the vocabulary measures of the WAIS (which are known to be reduced in DD). Participants also completed untimed and timed (fluency) tests of Word Identification (WI) and Word Attack (WA) subtests from the Woodcock Reading Mastery Test- Revised, and the Sight Word Efficiency Forms A + B (i.e., rate of word identification) and Phonemic Decoding Efficiency, Forms A + B (i.e., rate of decoding pseudo words) subtests from the Test of Word Reading Efficiency (TOWRE-II; Torgesen, Wagner, & Rashotte, 1999).

As expected, the two groups did not differ on the basis of age or non-verbal intelligence, as measured by the Raven test (see Table 1). However, compared with the control group, the DD group showed a clear profile of reading disability, with significant group differences on word reading and decoding skills, as evident on both rate and accuracy measures. In addition, compared with the control group, the DD group showed the characteristic deficits of reading difficulties, as manifest in phonological awareness (spoonerisms) and rapid naming (rapid automatized naming) tasks.

2.1.1. Hebrew readers

Six native Hebrew speakers were tested in Israel by the same experimenter. The three DD participants were recruited from the University Student Support Service at the University of Haifa, which provides support to students with learning disabilities. The diagnosis of dyslexia was performed by the University of Haifa Learning Disabilities Diagnostic Center using the MATAL test.[1] To assess dyslexia, the MATAL program calculates performance on several tests, including vocal text reading, nonword reading, phonemic deletion, phonemic count, rapid automatic naming, verbal fluency, syntactic awareness, and reading comprehension (for more information on the MATAL test, see Ben-Simon & Inbar-Weiss, 2012). The study received University of Haifa ethics approval, and written informed consent was obtained from participants.

The two groups did not differ in nonverbal IQ percentile scores, as measured by the Block Design subtest (Wechsler, 1997) (see Table 2). However, compared to the control group, the DD group exhibited a clear profile of reading disability conforming to the symptomatology of DD. The DD group differed significantly from the control group on word reading, decoding skills and phonological awareness (phoneme deletion, segmentation and parsing).

Table 1
Demographic and psychometric data of DD and control groups (English Readers).

	Group		
Measure	DD	Controls	p
Age (in years)	21.41	22.91	*n.s.*
Ravens	56.5	57.91	*n.s.*
Digit span[a]	11.08	13	*n.s.*
RAN objects[a]	101.5	114	*=0.07*
RAN colors[a]	96.66	110.58	*<0.01*[**]
RAN numbers[a]	105.5	112.33	*<0.01*[**]
RAN letters[a]	102.16	109.75	*<0.01*[**]
WRMT-R WI[a]	97.41	113.08	*<0.01*[**]
WRMT-R WA[a]	94.83	115.33	*<0.01*[**]
Towre SA (A + B)[a]	95.66	113.16	*<0.01*[**]
Towre PD (A + B)[a]	88.08	115.08	*<0.01*[**]
Spoonerism time	139.166	98.25	*<0.05*[*]
Spoonerism accuracy	8.25	11.33	*<0.01*[*]

[*] $p < 0.05$.
[**] $p < 0.01$.
[a] Standard scores, other raw scores. Numbers represent means.

Table 2
Demographic and psychometric data of DD and control groups (Hebrew readers).

	Group		
Measure	DD	Controls	p
Age (in years)	23.6	26.33	*n.s.*
Block Design[a]	12	12.67	*n.s.*
Digit span[a]	8.66	15	*<0.05*[*]
Oral words recognition	66.66	118.66	*<0.01*[**]
Oral non-words recognition	38.66	70	*<0.05*[*]
Parsing time	374.66	167.33	*<0.05*[*]
Parsing accuracy	41	44.66	*n.s.*
Segmentation time	110.66	65.66	*<0.05*[*]
Segmentation accuracy	10	16	*<0.01*[**]
Phoneme deletion time	246.33	84.66	*<0.01*[**]
Phoneme deletion accuracy	17.66	24.66	*<0.05*[*]

[*] $p < 0.05$.
[**] $p < 0.01$.
[a] Standard scores, other raw scores. Numbers represent means. Oral word recognition = number of words read correctly per minute. Oral non-words recognition = number of non-words read correctly per minute.

2.2. Stimuli

The stimuli used in the current study consisted of color pictures of male and female faces from the Max-Planck Face Database (Troje & Bülthoff, 1996). This database consists of a series of 3D models of real faces (no hair) in three viewpoints—full-frontal face (0°), right three-quarter (45°), and right profile (90°) (see Fig. 3a–c, examples of the three viewpoints). Each face was positioned on a black square background (7.5 × 7.5 cm). A total of 97 different faces were used for the experimental trials.

2.3. Procedure

Participants sat approximately 18 in. from the screen of the computer. On each trial, three stimuli appeared on a gray background: a target face (centered over fixation, 5.5 cm from the top of the screen) and two choices, to the left (9.5 cm from left, 16 cm from top) and right side of the fixation point (22.5 cm from left, 16 cm from top) (see Fig. 3). Each trial began with a fixation

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[1] The MATAL test is a standardized, computer-based, test battery for the diagnosis of learning disabilities in adults (Dyslexia, Dysgraphia, Dyscalculia, and Attention Deficit Disorder), developed by the Israeli National Institute for Testing and the Israeli Council for Higher Education. The MATAL includes 20 tests and 54 performance measures, all of which were validated and for which national norms were developed.

cross appearing for 250 ms, followed by the three stimuli, which remained on the screen until response. In the first part of the study, only upright faces, varying in viewpoint, were shown (see example in Fig. 3). The target could appear in one of three possible viewpoints — frontal (F), three-quarters (T) or profile (P). This was true of the choices as well, although in any given trial the two choice faces were in the same viewpoint (as shown in Fig. 1), resulting in 9 possible viewpoint combinations (3 target viewpoints × 3 choice viewpoints). The nine conditions were randomly mixed within each block of trials, with 30 trials per cell for a total of 270 trials. Trials were divided into two blocks with a short break between them. Participants pressed a left (B) or right key (N) using their dominant hand to indicate the side of the match to target.

Following this, participants completed an additional block of trials in which the target was always upright. On half the trials, the choices were both upright, whereas on the other half, the choices were both inverted (see Fig. 1). The target and choice faces were only shown in the frontal view (see Fig. 3e). Again, there were 40 trials per cell (inverted/upright) for a total of 80 trials.

This combination of conditions affords us the opportunity to compare the ability of the DD and control groups to discriminate faces as a function of viewpoint and inversion. Non-DD participants typically show a small cost in matching faces across viewpoint (frontal, three-quarters and profile views) and a cost in matching upright with inverted faces (Marotta, McKeeff, & Behrmann, 2002).

2.4. Results

We start by examining effects of inversion on face perception performance, and then consider effects of viewpoint.

2.4.1. Inverted vs. upright

The comparison of the DD and control groups used an analysis of variance (ANOVA) with inversion (upright vs. inverted) as a within-subjects factor and accuracy as the dependent measure. We first confirmed that control participants exhibited the typical face inversion effect and this was indeed the case: they were significantly less accurate matching an upright face to inverted faces ($M = 0.94$, S.E. = 0.01) than to upright faces ($M = 0.98$, S.E. = 0.01), $F(1, 14) = 8.09$, $p < 0.01$. This same pattern held for the DD group and there was neither a main effect of group nor an interaction of group × inversion, ($F < 1$). The same result was evident with RT (correct trials only) as the dependent measure: we confirmed the typical face inversion effect in the control group, $F(1, 14) = 36.07$, $p < 0.01$, with slowing when matching inverted ($M = 1362.21$, S.E. = 0.71.07) compared with upright faces. ($M = 1042.82$, S.E. = 42.35). Although the DD group was significantly slower overall than the control group, $F(1, 28) = 7.08$, $p < 0.05$, ($M = 1643.8$ ms and $M = 1202.5$ ms for the DD and control groups respectively), they too were slowed in the inverted compared with upright matches ($M = 1814.55$, S.E. = 204.87, $M = 1473.12$, S.E. = 114.28, respectively), and the interaction was not significant, $F(1, 28) = 0.04$, $p = 0.852$.

2.4.2. Matching across viewpoint

ANOVAs were conducted with viewpoint of the target (F, T, P) and of the choice faces (F, T, P) as within-participant factors, group (DD vs. controls) as a between-participants factor, and mean accuracy or RT (correct responses) as the dependent variable With accuracy as the dependent measure, there were no main effects or interactions with group, perhaps due to the extended exposure duration of the stimulus. With RT as the dependent measure (see Fig. 2), there was a main effect of group, with DD participants significantly slower than the control group, $F(1, 28) = 15.02$, $p < 0.01$ (mean: controls 1544.29 ms, *S.D.* = 399.74; DD 2187.76, *S.D.* = 569.39). Importantly, the three-way interaction of group × target viewpoint × choice viewpoint was significant, $F(4, 88) = 4.79$, $p < 0.01$.[2] Further post hoc analyses revealed that every pairwise condition differed significantly between DD and the controls; however, when the target and distractor did not have the same viewpoint, the RT difference between controls and DD was larger than when the target and distractors shared viewpoint (i.e., FFF, PPP or TTT in Fig. 2), $F(1, 28) = 5.12$, $p < 0.05$. This finding indicates that the DD group was slowed in all conditions but that the cost in matching across viewpoints was even greater in DD than in the controls.

In order to ensure that the group differences did not simply result from general slowing in the DD group over the course of the experiment (due to fatigue or attentional effects), we divided the trials into four bins (N = 270; approximately equal number of trials per bin) based on trial order. We then carried out an ANOVA with target viewpoint (F, T, P), choice viewpoint (F, T, P) and bin (1–4) as within-participant factors, and group (DD vs. controls) as a between-participants factor. No interaction of group with

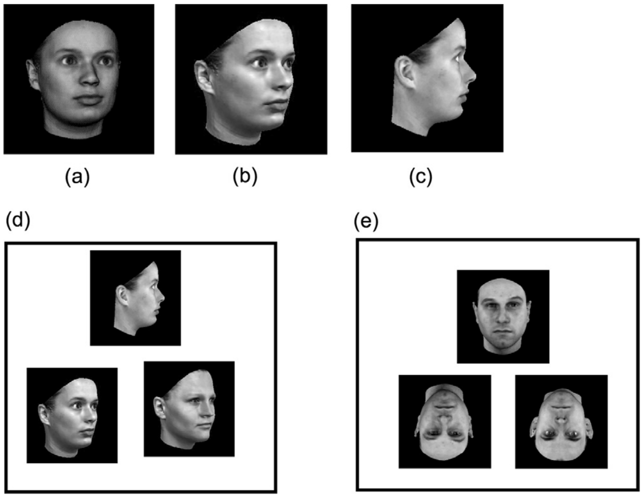

Fig. 1. Examples of stimuli and trial display from viewpoint manipulation face experiment. Examples of (a) Frontal (b) three-quarter and (c) profile view of a single face. (d) Display of trial containing an upright target on top and two upright choices for left/right decision below and (e) Display of trial containing an upright target on top and two inverted choices for left/right decision below.

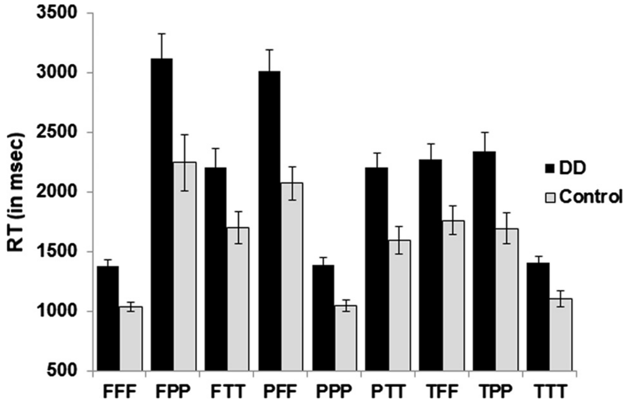

Fig. 2. Mean RT (and ±1 SE) of the control and the DD groups as a function of condition during face matching task. F = Frontal, T = three-quarters, P = profile.

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[2] When adding language as a factor to the ANOVA, this interaction was not modulated by participants' spoken language.

bin was found (all $F < 1.7$), indicating that the exaggerated slowing of the DD group compared to controls when viewpoint differed was present to an equivalent extent across the entire experiment.[3]

In summary, Experiment 1 revealed significantly slower performance by the DDs than controls when matching upright faces to both upright and inverted faces (with equivalent slowing due to inversion), and when matching faces that do or do not share viewpoints, albeit to a greater degree in the latter case.

3. Experiment 2: Simultaneous face and car discrimination

In this second experiment, our goal was twofold: to characterize further the face deficit in DD and to explore whether the deficit extends beyond words and faces to another visual category, namely cars. In this study, participants perform same/different discriminations between pairs of faces or pairs of cars where the perceptual similarity of the members of the pair is manipulated through a morphing procedure.

3.1. Participants

The participants were the same as in Experiment 1. We did, however, exclude those few participants who did not complete both face and car conditions of the study. This experiment included 20 participants.

3.2. Face/car morph

We used the stimuli and experimental procedure of Behrmann and Plaut (2012). Participants sat approximately 18 in. from the computer screen and viewed two face images, presented side-by-side simultaneously, for same/different discrimination. Faces and cars were presented in separate blocks of trials (see Fig. 3). The pair of stimuli could be either the same (25% of trials; N = 55) or different (75%; N = 165). The different trials were constructed to fall into three levels of difficulty (N = 55 in each). The *easy* condition consisted of a picture of two different faces (say Face A and Face B). For the *medium* condition, Face A was presented with a morph that comprised 33% of Face A and 66% of Face B, while in the *difficult* condition, Face A was presented with a morph that comprised 66% of Face A and 33% of Face B. For the medium and difficult trials, the two faces were morphed together using the MorphMan 4.0 software. The identical experiment was run using cars as the stimuli and the exact same procedure was used to construct the morphed cars. Each stimulus was roughly 2 × 3 in. (with faces longer vertically and cars longer horizontally). The midpoint of each stimulus was located 5.2 in. from the fixation point and subjects viewed the display at approximately 50 cm.

3.3. Procedure

Participants were informed that, on each trial, two stimuli (i.e., two faces or two cars) would appear simultaneously on either side of a red fixation dot, which occupied the center of the screen. Participants were told to fixate on the dot, and to decide whether the two stimuli were exactly the same or different in any way. If the pictures were different, participants were to press the "D" key on the keyboard, and if they were the same, they were to press the "S" key. The order of the trials was randomized within a block and participants were told to respond as accurately as possible.

3.4. Results

We conducted an analysis of variance (ANOVA) with stimulus type (face vs. car) and level of difficulty (easy, medium, and difficult) as within-participant factors, and group (DD vs. controls) as a between-participant factor, first using accuracy and then RT as the dependent variable. With accuracy, the main effect of group was not significant, $F(1, 26) = 1.15$, $p = 0.29$. The main effect of level of difficulty was significant $F(2, 52) = 381.6$, $p < 0.01$, and there was a significant linear trend across levels, $F(1, 26) = 376.1$, $p < 0.01$. The interaction of stimulus type and group was significant, $F(2, 44) = 6.75$, $p < 0.05$, with the DD participants performing significantly more poorly on face discrimination than controls, $F(1, 26) = 4.65$, $p < 0.05$, whereas no significant group differences were observed while discriminating cars, $F < 1$. With RT, there was a main effect of level of difficulty, $F(2, 52) = 26.28$, $p < 0.01$, indicating a significant linear trend, $F(1, 26) = 29.52$, $p < 0.01$. Additionally, no significant interactions or main effects with group were found, perhaps unsurprisingly as exposure duration was unlimited (minimum $p = 0.124$).

In summary, this study revealed that performance for the DD versus control group was poorer for faces but not for cars. This finding indicates that the observed decrement in the DD group for word and face perception is not obviously attributable to a general visual processing impairment and, rather, may be limited to words and faces.

4. Experiment 3: Hemispheric organization of word and faces

The findings thus far reveal that the individuals with DD performed significantly more poorly than controls on both word and face recognition. This impairment is not fully general, however, as indicated by the normal performance of the DD group on discriminating cars. The final experiment evaluates whether DD alters the typical hemispheric organization of word, face and car perception—with words stronger in the LH, faces stronger in the RH, and cars equally strong in both—by measuring performance in matching stimuli presented in the left or right visual fields. For ease of understanding, we will refer to the results in terms of both visual field (VF) and hemisphere (RVF/LH or LVF/RH).

4.1. Participants

Thirty participants, 15 with DD (6F, 9M) and 15 control individuals (6F, 9M) participated in this experiment. Twenty-two participants were native English speakers and 8 participants were native Hebrew speakers. Nine DD participants and six controls, all native English speakers, participated in the face experiments reported earlier, and the new DD (2) and control (5) participants were assessed using the same standardized measures used previously. The groups of DD and control participants did not differ on the basis of age or intelligence (see Table 3). The DD group differed significantly from the control group on word reading and decoding skills in both rate and accuracy measures, and showed the characteristic deficits in the three major phonological domains: phonological awareness (spoonerisms), verbal short-term memory (digit span) and rapid naming (rapid automatized naming).

The group of Hebrew DD participants did not differ from the controls in nonverbal IQ percentile scores, as measured by the Block Design subtest (Wechsler, 1997) (see Table 4). However, compared to the controls, the DD group exhibited a clear profile

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[3] We recognize that these analyses (incorporating bin as a factor) may not be perfectly controlled: trials were randomized from each condition throughout the experiment, so it is possible that the bins had slightly different distributions of trials across conditions. This is not surprising as the experiment was not originally designed to control the sampling of trials over time. Nevertheless, the absence of any interaction with bin and the presence of the three-way interaction noted above suggest that the group differences are not a product of a generalized effect in the DD group.

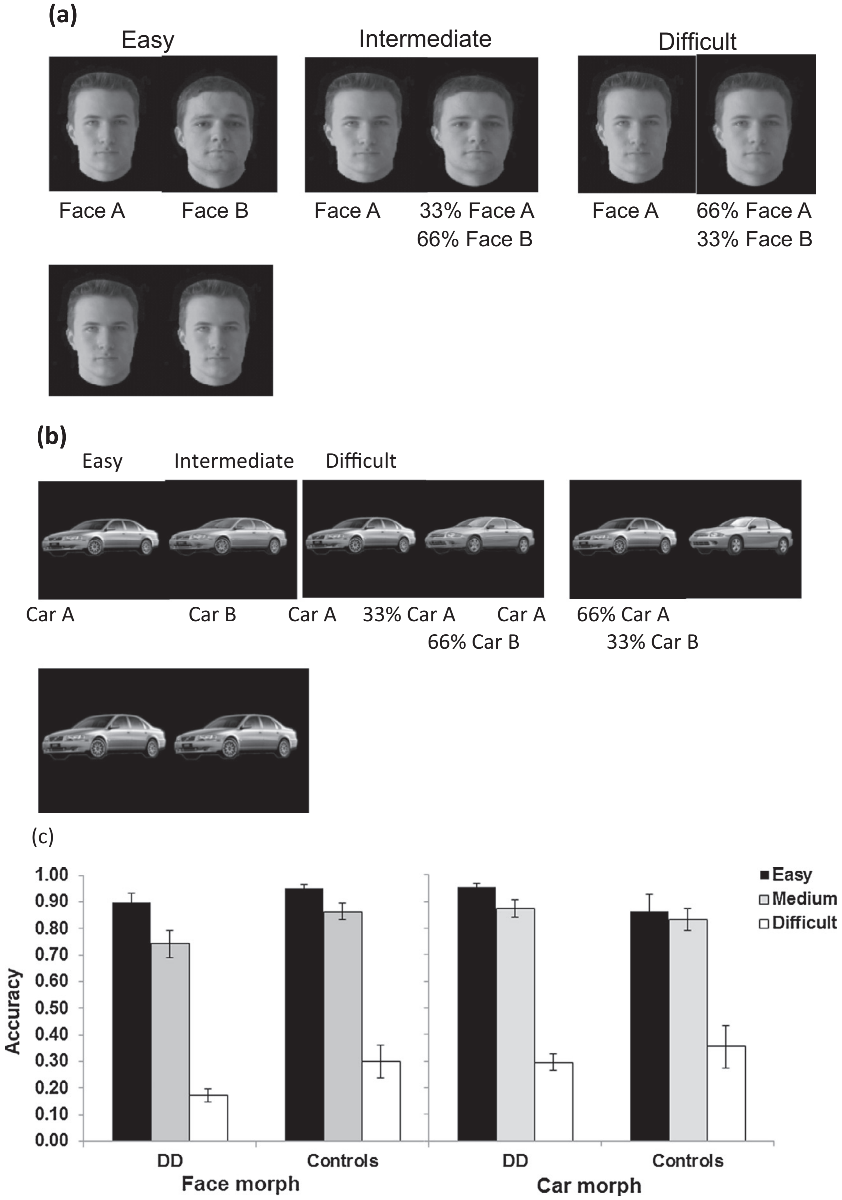

Fig. 3. (a) Example trials: face discrimination. Top row: Different trials, from left to right (i) an easy discrimination pair, (ii) an intermediate discrimination pair and (4) a difficult discrimination pair; Bottom row: Example same trial. (**b**): Example trials: car discrimination. Top row: Different trials, from left to right (i) an easy discrimination pair, (ii) an intermediate discrimination pair and (iii) a difficult discrimination pair; Bottom row: Same trial. (c) Mean accuracy (and ±1 SE) as a function of level for the DD and control groups during face/car discrimination.

of reading disability, with poorer performance on word reading, decoding skills and phonological awareness (phoneme deletion, segmentation and parsing).

4.2. Stimuli

Thirty male and thirty female face images from the Face-Place Database Project (Copyright 2008, Dr. M. Tarr) were used in this experiment. All faces were forward facing with neutral expression (see example in Fig. 4a). The faces were cropped to remove hair cues and presented in grayscale against a black background. Stimuli were 1 in. wide and 1.5 in. high, yielding visual angles of 4.8° and 3.2°, respectively. On each trial, the pair of faces matched on gender.

The word stimuli consisted of 60 four- letter words (30 pairs), taken from a study by Dundas, Plaut, and Behrmann (2013) and presented in gray, Arial, 18-point font against a black background. Stimuli were approximately 1 in. wide and 0.5 in. high, yielding visual angles of 1.6° and 3.2°, respectively. Pairs were matched so that the words differed by one of their interior letters, with 15 of the pairs having a different 2nd letter and 15 having a different 3rd letter (see example pair in Fig. 4a). The mean word frequency in English was 53.89 per million [range 0.118–578.5] and the mean summed positional bigram frequency was 778.6 per million [range 83.48–2000.66] (Marcus, Marcinkiewicz, & Santorini, 1993). Note that the face and word stimuli elicited a LVF/RH advantage for faces and a RVF/LH advantage for words, as expected, in a previous study (Dundas et al., 2013).

In addition to faces and words, we also included cars, both to provide another measure of visual discrimination in DD relative to controls and also to use as a control benchmark of hemispheric specialization, as these car stimuli do not yield an advantage in either hemisphere (Dundas et al., 2013). The 60-car stimuli were presented in gray scale at a three-quarter left-front facing view.

Table 3
Demographic and psychometric data of DD and control groups (English readers) in Experiment 3.

Measure	Group DD	 Controls	 p
Age (in years)	21.54	22.63	*n.s.*
Ravens	56.45	58.18	*n.s.*
Digit span[a]	10.9	13.5	*<0.05**
RAN objects[a]	103.45	117.45	*<0.05**
RAN colors[a]	100.09	110.45	*<0.05**
RAN numbers[a]	106.90	114.18	*<0.01***
RAN letters[a]	103.54	112.27	*<0.01***
WRMT-R WI[a]	99.81	113.72	*<0.01***
WRMT-R WA[a]	98.72	115.63	*<0.01***
Towre SA (A + B)[a]	100.09	113.81	*<0.01***
Towre PD (A + B)[a]	91.36	115.45	*<0.01***
Spoonerism time	132.09	95.81	*<0.05**
Spoonerism accuracy	8.45	11.27	*<0.05**

* $p < 0.05$.
** $p < 0.01$.
[a] Standard scores, other raw scores. Numbers represent means.

Table 4
Demographic and Psychometric data of DD and control groups (Hebrew readers) in Experiment 3.

Measure	Group DD	 Controls	 p
Age (in years)	24.5	27	*n.s.*
Block design[a]	12.25	11.5	*n.s.*
Digit span[a]	8.25	14.25	*<0.05**
Oral words recognition	64.25	127.25	*<0.01***
Oral non-words recognition	36.25	70	*<0.01***
Parsing time	376.6	181.75	*<0.01***
Parsing accuracy	41	44.5	*n.s.*
Segmentation time	107.67	80.5	*n.s.*
Segmentation accuracy	10.75	15.5	*<0.01***
Phoneme deletion time	258.04	89.75	*<0.01***
Phoneme deletion accuracy	18	24.75	*<0.01***

* $p < 0.05$.
** $p < 0.01$.
[a] Standard scores, other raw scores. Numbers represent means. Oral word recognition = number of words read correctly per minute. Oral non-words recognition = number of non-words read correctly per minute.

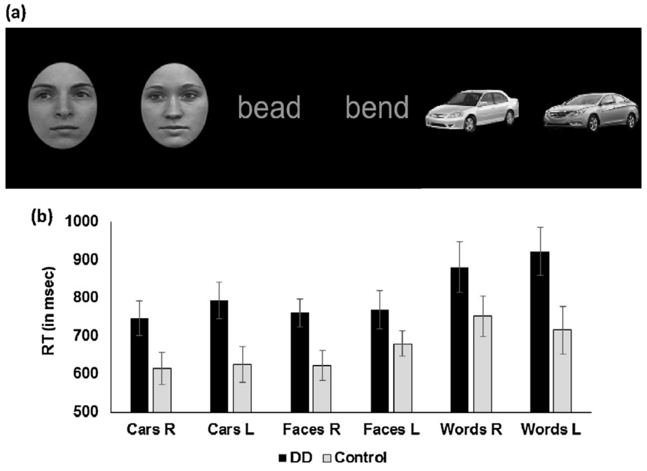

Fig. 4. **(a)** Example of a pair of faces, words used in the half-field lateralization study **(b)** Mean RT (and ±1 SE) for DD and control groups as a function of stimulus type and hemi-field.

Stimuli were approximately 1.75 in. wide and 1 in. high, yielding visual angles of 5.57° and 3.2°, respectively (see Fig. 6a).

4.3. Procedure

We followed the exact procedure reported in Dundas et al. (2013). The experiment was run on a laptop computer using E-prime software (Schneider, Eschman, Zuccolotto, & Guide, 2002). Participants sat approximately 18 in. from the screen. Words, faces and cars were presented in separate blocks of trials. Participants viewed a central fixation cross whose duration ranged between 1500 and 2500 ms. Following the offset of the fixation cross, a centrally presented stimulus (word, face or car) appeared for 750 ms and was followed immediately by a second stimulus of the same type (word, face, car) presented for 150 ms in either the LVF or RVF, with the center of the stimuli being 5.3° from fixation. Participants were instructed to keep their gaze fixated centrally throughout the experiment and to respond by pressing one of two buttons to indicate whether the second stimulus was identical to the first or not (same/different judgment). The fixation cross appeared following the button press and indicated the start of the next trial.

The presentation of stimuli in the LVF or RVF was randomized per subject with equiprobable presentation in each field within a block. For each class of stimuli, there were 96 trials, which were split into three blocks to give participants a rest between blocks. The presentation order of the blocks of word, face and cars was counterbalanced across participants. In addition to the instruction to maintain fixation, the brief exposure duration of the 'probe' in the half-field ensured that a saccade away from fixation was highly unlikely. Therefore, this design allowed us to examine the relative contribution of the LH and RH to the processing of different visual classes.

4.4. Results

ANOVAs were conducted with stimulus type (words, faces, cars) and hemifield (LVF, RVF) as within-participant factors, and group (DD vs. controls) as a between-participants factor, first using accuracy and then using RT for correct trials as the dependent measure.

With accuracy, there was a main effect of group, $F(1, 28) = 7.11$, $p < 0.01$, such that DD participants were less accurate than control participants. There was, however, an interaction of stimulus type × group, $F(2, 56) = 5.34$, $p < 0.01$: whereas the controls and DDs performed equally well on cars (both 0.88), the controls performed significantly better than the DDs on both stimulus types but to an even greater degree on faces (controls vs DD: 0.92 versus 0.83, $p < 0.01$) than on words (controls versus DD: 0.90 versus 0.83, $p < 0.05$). The stimulus type and hemifield interaction was significant, $F(2, 56) = 9.92$, $p < 0.01$, such that for word stimuli, participants were more accurate when words were presented in the right than left hemifield $F(1, 28) = 12.08$, $p < 0.01$. No significant differences in accuracy were observed for face stimuli, $F(1, 28) = 2.83$, $p = 0.1$ or for car stimuli, $F < 1$. Note that neither the hemifield × group interaction nor the hemifield × stimuli × group interaction were significant (minimum $p = 0.19$).

With RT as the dependent measure, there was a main effect of group, $F(1, 28) = 5.79$, $p < 0.05$, with slower responses overall for the DD than the control group. The main effect of stimulus type was significant, $F(2, 56) = 13.90$, $p < 0.01$, with slower responses observed in the word stimuli compared with face and car stimuli, $F(1, 28) = 22.36$, $p < 0.01$. No differences in RT were observed between car and face stimuli, $F < 1$. The stimulus type × group interaction was not significant, $F < 1$ but the three-way interaction of group, stimulus type, and hemifield was marginally significant, $F(1, 28) = 2.44$, $p = 0.09$. Because we had an a priori interest in the visual field differences for the two groups, we conducted post hoc tests on the marginal three-way interaction. These analyses revealed that control participants responded faster when face were presented to the left than right visual field (RVF), F (1, 14) = 5.04, $p < 0.01$ (for LVF M = 621.2, S.E. = 37.1 and for RVF, M = 680.94, S.E. = 50.35) and this pattern was reversed for word stimuli, F(1, 14) = 4.2, p = 0.06 (M = 752.69, S.E. = 65.99 for the LVF and M = 715.39, S.E. = 62.699 for RVF). As expected, there were no differences for car stimuli, $F < 1$. In contrast with the findings from the controls, DD participants did not show the expected lateralization pattern for word (M = 992.59, S.E. = 62.44 for the LVF and M = 881.31, S.E. = 52.62, for the RVF) or face stimuli (M = 770.08, S.E. = 33.61 for the LVF and M = 760.88, S.E. = 39.50 for the RVF).

In summary, compared with the controls, DD participants were not only slower and less accurate in matching words but were also slower and less accurate in matching faces. As in the previous experiment, there was no difference across the groups in matching cars. In addition, whereas the typical lateralization pattern was observed among control participants, there was no clear RT hemispheric lateralization for either faces or words stimuli in those with DD.

5. General discussion

The purpose of the current research was to inform the ongoing debate regarding the selectivity of the deficit in developmental dyslexia (DD), by examining whether the disorder is restricted to the processing of written words or is more general, affecting the recognition of other visual stimuli, such as faces, as well.

5.1. DD impaired in face perception

Our standardized tests confirmed that the DD individuals met the criteria for DD and performed more poorly on word processing compared with controls. Importantly, impaired processing in DD was not limited to words but was also evident for faces over multiple, different experimental paradigms. First, although individuals with DD showed the normal face inversion effect (poorer performance on inverted vs. upright faces), as was also the case with individuals with alexia following left VOT damage (Behrmann & Plaut, 2013), they matched faces more slowly than controls. DDs also showed an exaggerated cost, relative to controls, when target and distractor differed in viewpoint. Moreover, DD participants were significantly poorer than controls at discriminating between faces morphed to be more similar to one another. These findings provide clear evidence from several different tasks for an impairment in face perception in DD. Importantly this deficit did not extend to all visual categories, as the DDs performed equivalently to the controls in discriminating between images of cars, across all levels of difficulty.

The few previous investigations that have targeted more perceptual aspects of face perception have also revealed differences in the neural and behavioral profiles of DD and control participants. For example, in a MEG study that characterized both behavioral and electrophysiological responses, DD individuals were both less accurate in a facial recognition task and were slower in judging the similarity of faces (Tarkiainen, Helenius, & Salmelin, 2003). These same DD individuals showed reduced activation of the right parietotemporal cortex at about 250 ms after stimulus onset. Also, a relatively recent meta-analysis of fMRI studies identified a different neural pattern in DD compared with controls, but in this case, the study revealed that the most consistent hypoactivation was found in the left occipitotemporal region. (Richlan, Kronbichler, & Wimmer, 2013) This finding is also congruent with experiments that implicate an early failure to engage this system in children with dyslexia (Maurer et al., 2007) and in kindergartners bearing a genetic predisposition for the disorder (Raschle et al., 2012).

It is important to consider how the current findings can be reconciled with previous studies that have yielded contradictory results. Some studies have also found impairments in face processing by individuals with DD (Sigurdardottir et al., 2015; Tarkiainen et al., 2003), as we have, but a number of other studies have not (Brachacki et al., 1994; Rüsseler et al., 2003; Smith-Spark & Moore, 2009). One factor that may have contributed to discrepancies in the literature concerns differences in task demands. For example, some studies that failed to reveal differences in face processing in DD and controls (Brachacki et al., 1994; Rüsseler et al., 2003) employed a different methodological approach in which the memory or naming of faces, rather than perceptual processing per se, was tested with stimuli displayed under unlimited exposure duration.

There is also a discrepancy between the apparently normal performance of our DD participants on car discrimination and the results from Sigurdardottir et al. (2015) who identified decrements in DD individuals across a range of object tasks, including butterflies, birds, planes and cars. The discrepancy across that study and the present one result might arise from the methodological differences. Notably, in Sigurdardottir et al. (2015), there was a memory component: as in the Cambridge Face Memory Test, participants were exposed to a set of exemplars (for example, in the butterfly condition, they saw six different butterflies) and then during the experimental trials, they were shown three exemplars and had to identify which of the three was 'old' (has been studies previously). In the current study, the object discrimination was perceptual and the stimuli remained exposed throughout the trial, thereby obviating any need for memory.

It is important to address how our findings and account relate to the substantial documented heterogeneity of symptoms (and presumed causes) of DD. A prominent hypothesis is that DD arises from a primary deficit in access to, and manipulation of, phonological representations (Snowling, 2000) and, indeed, phonological deficits are among the most common symptoms associated with DD (Vellutino et al., 2004). Nevertheless, there are many studies demonstrating additional visual, attentional, and learning deficits in DD (Démonet et al., 2004). As a result, the phonological deficit hypothesis may not serve as the sole explanatory framework to account for DD (Bosse, Tainturier, & Valdois, 2007; Hari & Renvall, 2001; Nicolson, Fawcett, & Dean, 2001). One potential alternative explanation might implicate a reduction in visual attention span (VAS) (Bosse et al., 2007). Although people with DD show impaired performance on attentional tasks, the exact mechanism to account for impaired attentional skills is still highly debated. The Visual Attentional Span (VAS) hypothesis suggests reduced visual attentional resources (Bosse et al., 2007) but there are many demonstrations as well suggesting a mechanism of increased diffusivity of attention (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008). A reduction in VAS, however, does not seem to be the right explanation either as this framework cannot account for intact car performance observed across two experiments in the present research.

The current results also only partially uphold theories postulating a fully general visual deficit. For example, Goswami (2015) and similarly Olulade, Napoliello, & Eden (2013) have argued that sensory deficits in dyslexia may arise as a consequence of reduced reading experience. The claim is that sensory processing deficits are not causally related to the neurocognitive basis of dyslexia, but rather arise as a consequence of reading less. Since our study examined adults with dyslexia, this is an important point of consideration. If reading less were to affect visual processing more generally, it may lead to altered face perception in adulthood unrelated to the causal basis of dyslexia. If this hypothesis holds, reduced reading experience might be expected to affect visual processing of all categories (including that of cars) rather than affecting some while leaving the other intact. Our results indicate that participants with dyslexia are impaired at face and word processing but not at car processing. Thus, although the deficit does extend beyond orthographic processing, there does not appear to be an across-the-board impairment in sensory and perceptual representations in DD. We posit that DDs' impaired performance on face and word stimuli can be accounted for by difficulties in learning or gaining perceptual expertise (and the ability to make fine-grained discrimination among a group of homogeneous exemplars). Perceptual expertise is especially relevant for face and word stimuli since both are acquired through development and of high utility during daily life (compared with car processing or other stimuli) (Palmeri, Wong, & Gauthier, 2004). That the ability to recognize face and word categories stays effortful, demanding, prone to interference, and less automatic in those with DD, is consistent with an increasing body of evidence suggesting that DD reflects a more general learning disorder especially of representations that are homogeneous and encountered with high frequency (Gabay & Holt, 2015; Nicolson & Fawcett, 2007, 2011). In sum, our cautious conclusion is that this approach does not necessarily suggest that perceptual processing per se is the underlying cause of DD but, rather, that the profile we observe here may be the end product of disrupted skill acquisition processes that are especially relevant for word and face recognition. While it might be reasonable to think that reading might cause competition for brain areas and actually decrease face processing, as we have suggested, some alternative process cannot be ruled out. Ultimately, as Goswami (2015) advocates, longitudinal studies are critically needed in order to examine whether beginning readers who go on to have dyslexia also have a weakness in face processing and in order to make progress in establishing causality.

That our findings of impaired face processing in DD held at a group level despite the presumed heterogeneity of our DD population speaks to the pervasiveness of the effects. This result notwithstanding, future research should attempt to determine whether particular subtypes of DD exhibit greater impairment in face processing compared to others. At first glance, it might seem obvious that those with more direct visual problems would have the greatest problems with face processing. However, it is important to keep in mind that visual word representations develop not only under the influence of bottom-up visual information but also on the basis of interacting with top-down language/phonological information (Price & Devlin, 2011). Additionally, our study includes a group of high-achieving young adults with dyslexia. While, on the one hand, our results are all the stronger for the deficit being clearly evident in a group of high-achieving young adults with dyslexia, on the other hand, caution is warranted in extending these results broadly. Further work is needed to determine whether these impairments extend to samples of dyslexics who are not university students.

The current data are also consistent with an accumulating body of evidence establishing a close relationship between face and word processing, and distributed rather than domain-specific networks for word and face processing. For example, patients with prosopagnosia and pure alexia exhibited processing impairments that were not restricted to the domain of expected impairment (Behrmann & Plaut, 2012); thus, individuals with pure alexia following a unilateral LH lesion also showed a deficit for face recognition, albeit not as great as in individuals with prosopagnosia following a unilateral RH lesion, and the prosopagnosics exhibited an impairment in word recognition, although, again, not as severe as in the pure alexics. Also, and perhaps not surprisingly in light of the behavioral co-occurrences describe here, in a recent neuroimaging study, 10-year-olds with DD showed reduced activation to words in the left VWFA and to faces in the right FFA, compared to controls (Monzalvo, Fluss, Billard, Dehaene, & Dehaene-Lambertz, 2012). In contrast, both groups showed similar right-lateralization for other categories such as chalkboards and houses using whole brain asymmetry analyses.

In addition to elucidating that DD individuals are impaired in visual processing faces as well as cars, there are also preliminary findings supporting altered hemispheric organization of word and face processing in DD. In particular, whereas we observed the typical pattern of hemispheric lateralization among control participants, with faster RTs when words were presented to the RVF than LVF, and faster RT responses for faces presented to the LVF than RVF, this pattern was not observed for the DD group. Instead, the DDs performed equivalently for words presented to both hemifields and for faces presented to both hemifields. It might be the case that the lack of word lateralization in DD implies that there was a lack of pressure to lateralize face processing. Nevertheless, such a deficit might arise in visual areas or, perhaps more likely, in phonological representations and weakened lateralization for language (for recent review, see Bishop, 2013). In a related study (Collins, Dundas, Gabay, Plaut & Behrmann, under review), we examined the electrophysiological waveforms (ERP) generated in response to discriminating words and discriminating faces in a group of DD adults and matched controls as well as in a group of adults with congenital prosopagnosia (CP), a developmental impairment that affects the recognition of faces. The analysis of the N170 component revealed the expected pattern of lateralization in the typical controls: the response potential to words was stronger (i.e., more negative) in the LH than RH and the response potential to faces was stronger in the RH than LH. The CP group showed the typical ERP superiority for words in the LH but did not show the typical RH superiority for faces. In contrast, in the DDs, there was neither a difference in the N170 event-related potential between the two hemispheres for words, nor was there a difference between the two hemispheres for faces. These findings closely match the results obtained in the half-field study employed here. We also note that the alteration in hemispheric organization is consistent with the finding that a group of left-handed individuals (in whom language lateralization is more variable than in right-handed individuals) also show atypical lateralization of faces (Dundas, Plaut, & Behrmann, 2015).

In summary, detailed behavioral testing of individuals with DD revealed concurrent deficits in face and word processing. The particular association of word and face processing deficits is difficult to reconcile with a strict phonological-based account and is more consistent with domain general accounts of DD (Nicolson & Fawcett, 2007, 2010, 2011). The results are also surprising under the standard view that word and face domains are processed by independent mechanisms, and are more compatible with a recent theoretical development in which word and face representations compete during development to be near high-acuity visual information (Behrmann & Plaut, 2013; Plaut & Behrmann, 2011; Behrmann & Plaut, 2015).

Disclosure statement

No potential conflict of interest was reported by the authors.

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