Cerebral Cortex April 2014;24:1102–1118
doi:10.1093/cercor/bhs390
Advance Access publication December 18, 2012

Bilateral Hemispheric Processing of Words and Faces: Evidence from Word Impairments in Prosopagnosia and Face Impairments in Pure Alexia

Marlene Behrmann and David C. Plaut

Department of Psychology, Center for the Neural Basis of Cognition, Carnegie Mellon University, Pittsburgh, PA 15213-3890, USA

Address correspondence to Dr Marlene Behrmann. Email: behrmann@cmu.edu

Considerable research has supported the view that faces and words are subserved by independent neural mechanisms located in the ventral visual cortex in opposite hemispheres. On this view, right hemisphere ventral lesions that impair face recognition (prosopagnosia) should leave word recognition unaffected, and left hemisphere ventral lesions that impair word recognition (pure alexia) should leave face recognition unaffected. The current study shows that neither of these predictions was upheld. A series of experiments characterizing speed and accuracy of word and face recognition were conducted in 7 patients (4 pure alexic, 3 prosopagnosic) and matched controls. Prosopagnosic patients revealed mild but reliable word recognition deficits, and pure alexic patients demonstrated mild but reliable face recognition deficits. The apparent comingling of face and word mechanisms is unexpected from a domain-specific perspective, but follows naturally as a consequence of an interactive, learning-based account in which neural processes for both faces and words are the result of an optimization procedure embodying specific computational principles and constraints.

Keywords: face recognition, hemispheric specialization, lateralization of function, prosopagnosia, pure alexia, word recognition

Introduction

Two opposing theoretical perspectives have been offered to explain the manner by which biological structures, such as the human ventral visual cortex, come to be functionally optimized in the service of visual object recognition. The first perspective argues that there are distinct cortical modules or regions, which mediate behavioral processes, such as face, or word, or object recognition, in a domain-specific manner (Kanwisher 2010; McKone and Robbins 2011; McKone et al., 2012). Consistent with this approach are the findings that different areas in ventral visual cortex respond selectively to particular categories of visual stimuli: for example, as evident from many fMRI studies, the fusiform face area (FFA) is selectively activated in response to faces (Puce et al. 1995; Kanwisher et al. 1997), the parahippocampal place area to scenes (Epstein et al. 1999; Epstein 2011; Sewards 2011), and the extrastriate body area and fusiform body area to human bodies and body parts (Peelen and Downing 2005; Schwarzlose et al. 2005; Willems et al. 2010). Indeed, in each of these regions, the blood oxygen level–dependent (BOLD) response for the preferred category is about twice that for the nonpreferred category. Moreover, these domain-selective responses are evident in most individuals and these patterns of selectivity are observed across many different studies conducted by many different investigators using a host of different paradigms.

The second perspective acknowledges the apparent selectivity of neural areas for certain visual classes, but argues that this selectivity need not implicate specialized modules per se. On this account, there exists a many-to-many arrangement, in which multiple regions mediate the recognition of a particular object type (e.g., faces) and in which any single region represents multiple object types, albeit to varying degrees (Ishai Ungerleider, Haxby et al. 2000). Consistent with this perspective, fMRI studies have demonstrated that, in addition to the FFA, multiple cortical regions evince face selectivity, including the occipital face area (OFA) (Gauthier et al. 2000), the posterior superior temporal sulcus (STS; Haxby et al. 2000) and the anterior temporal lobe (Kriegeskorte et al. 2007; Rajimehr et al. 2009) [see also (Gobbini and Haxby 2007; Avidan and Behrmann 2009; Atkinson and Adolphs 2011)]. Additionally, even highly selective regions, such as the FFA, evince a BOLD response to different object classes, albeit with lesser activation (Gauthier, Tarr et al. 1999; Ishai, Ungerleider, Martin et al. 2000; Grill-Spector et al. 2006; Hanson and Schmidt 2011; Haxby et al. 2011; Nestor et al. 2011). Thus, even within a region, specialization is more graded than binary and a particular region may be optimized for, but not necessarily devoted to, a distinct cognitive function (Haxby et al. 1991).

In the current article, we examine the extent of the specificity of the neural substrate subserving the recognition of 2 classes of objects, words, and faces. We chose these 2 classes because, intuitively, they would seem to be diametrically opposed, obviously differing in overt geometry and image statistics. Additionally, faces and words diverge substantially in their acquisition, as face recognition develops incidentally whereas, for most individuals, word recognition is acquired through specific instruction in a more formal schooling environment. Finally, the evolutionary status of words and faces are fundamentally different: reading is a relatively recent invention, introduced approximately 5400 years ago (Dehaene and Cohen 2007), and, until roughly 150 years ago, its use was limited to a minority of the human population before basic education for the mass population was introduced (at least in the Western "developed" nations). This evolutionary time course is obviously not the case for face recognition.

Domain Specificity: Words and Faces

From a domain-specific perspective, words and faces are each assumed to be subserved by a particular, distinct cortical region. The visual word form area (VWFA), considered the pre-eminent region underlying word recognition is located roughly at Talairach coordinates $x = -43$, $y = -54$, $z = -12$ in the left hemisphere, and is identifiable even in single subjects (Puce et al. 1996). The VWFA is activated by visual but not auditory words (Cohen and Dehaene 2004; Dehaene et al.

2005; although see Price and Devlin 2011), to a greater degree for letters than digits (Polk et al. 2002) or visually equivalent pseudoletters (Allison et al. 1994; Cohen and Dehaene 2004). VWFA activation is rapid, occurring around 150–200 ms postonset, as shown by evoked response potential (ERP) (McCandliss et al. 2003) and magnetoencephalography (Marinkovic et al. 2003), and its response is relatively insensitive to retinal position and stimulus font, size, or case (Polk and Farah 2002).

Homologously, the FFA, with peak activation at roughly Talairach coordinates $x = 40$, $y = -55$, $z = -10$ in the right hemisphere, responds more strongly to upright than inverted faces or other nonface objects (Sergent and Signoret 1992; Kanwisher et al. 1997, 1999; Schwarzlose et al. 2005). FFA activation is highly stable within individuals and is correlated with face recognition ability (Yovel et al. 2008).

Additional support for regionally selective signatures for words and for faces comes from neuropsychological investigations in which patients with unilateral lesions to the VWFA, on the left, or the FFA, on the right, evince specific behavioral impairments (Kleinschmidt and Cohen 2006). Thus, patients with a lesion to the left occipital temporal area, specifically along the fusiform and adjacent lingual gyri with possible incursion to the inferior longitudinal fasciculus (Feinberg et al. 1994; Cohen et al. 2003, 2004; Salvan et al. 2004; Barton 2011) have "pure alexia." These patients read in a halting, laborious fashion, using a letter-by-letter strategy, and there is a linear relationship between their speed (or accuracy) and the length of the word or letter string (e.g., see Montant and Behrmann 2001).

Correspondingly, a lesion to the inferior right temporal lobe results in prosopagnosia (Bodamer 1947; Sergent and Signoret 1992; Marotta et al. 2001; Barton 2011), an impairment in face recognition despite intact sensory vision and normal semantic and naming performance. Salient cues such as facial hair, clothing, or hairstyle are used to identify individuals, and gait and voice serve as useful complementary cues. Most cases of prosopagnosia have damage in the vicinity of the lingual and fusiform gyri (Meadows 1974; Damasio et al. 1982), a conclusion supported by a meta-analysis (Bouvier and Engel 2006) and survey of cases (Barton 2008). Although some cases have bilateral lesions, the growing consensus is that a right hemisphere lesion alone is sufficient to give rise to prosopagnosia.

Distributed Circuits: Words and Faces

In contrast with the claim that the cortical structures responsible for human visual recognition contain domain-specific regions, others have argued for more distributed systems in which subregions are only partially specialized for particular stimulus classes. For example, there is a growing body of work showing that words activate a large swath of ventral cortex, beyond just the VWFA itself (Nazir et al. 2004; Nestor et al. 2011), with 1 hypothesis suggesting that this posterior-to-anterior axis serves to represent letters in increasing larger combinations (Vinckier et al. 2007; Dehaene and Cohen 2011) (for earlier ideas consistent with psychological networks for words and faces, see Morton and Patterson 1980; Bruce and Young 1986). Exposure to letter-like inputs affects even the tuning properties of V1 neurons (Sigman et al. 2005). Consistent with the graded organization of even a single region, the VWFA is activated not just by orthographic input but also by other stimuli, for example, line drawings (Kherif, et al. 2011; Price and Devlin 2003; Wright et al. 2008) and pictures (Braet et al. 2012), and even faces (Nestor et al. 2013). Predictably then, pure alexic patients with VWFA lesions are impaired in their perception of digits (Starrfelt and Behrmann 2011) and objects (e.g., Behrmann et al. 1998; Starrfelt and Gerlach 2007; Starrfelt et al. 2009; Roberts et al. 2013), as well.

Similarly, recent studies have provided evidence that face recognition is mediated by a distributed neural network consisting of a number of areas, including the FFA, a lateral OFA, and the STS, as well as anterior extended regions including the anterior temporal lobe (Kriegeskorte et al. 2007; Avidan and Behrmann 2009; Rajimehr et al. 2009; Thomas et al. 2009; Nestor et al. 2011, 2012). Moreover, a focal lesion to regions other than the FFA, such as to the anterior temporal lobe (Bukach et al. 2006; Williams et al. 2006; Barton 2008) can result in prosopagnosia, as can a structural disconnection between the FFA and this anterior temporal lobe region (Thomas et al. 2008), although the relative contribution of each area itself remains to be determined fully. Patients with prosopagnosia may also show impaired recognition of other stimulus classes, such as Greebles or common objects (Behrmann et al. 2005).

Lateralization

Although there seems to be increasing agreement that the recognition of words and of faces are each mediated by a more distributed than modular system, the current view is still that these 2 stimulus classes are subserved by separate and independent circuits, with words lateralized to the left (Dehaene and Cohen 2011) and faces lateralized to the right hemisphere (Kanwisher et al. 1997).

Close scrutiny of some imaging studies, however, suggests that these 2 apparently disparate classes of visual stimuli might be less lateralized than assumed to date. For example, many fMRI and ERP studies show bilateral activation for words and for faces, albeit usually with greater activation for words on the left and faces on the right side of the brain (Sergent et al. 1992; Puce et al. 1996; Kanwisher et al. 1997; Tagamets et al. 2000; Hasson et al. 2002; Kronbichler et al. 2004; Price and Mechelli 2005; Nestor et al. 2011). Consistent with this, prosopagnosia is more severe following bilateral than unilateral right lesions (Barton 2008), implicating a left hemisphere contribution to face recognition, and prosopagnosia has been reported in a right-hander subsequent to a left hemisphere lesion (Mattson et al. 2000; Anaki et al. 2007) (for recent review of lesions in prosopagnosia and a theoretical proposal, see Gainotti and Marra 2011). Conversely, the right hemisphere appears to play a functional role in word recognition as pure alexia has been reported in a right-hander after a unilateral right occipitotemporal lesion (Ogden 1984; Davous and Boller 1994). One final example is of a patient with pure alexia whose recovered reading was disrupted by transcranial magnetic stimulation to the right but not to the left hemisphere (Coslett and Monsul 1994).

In light of the possible engagement not only of the preferred hemisphere (left for words, right for faces) for recognition of words and faces but also, albeit to a lesser degree, of the nonpreferred hemisphere (left for faces, right for words),

we examined both the word and face recognition skills of individuals with either pure alexia following a left hemisphere lesion to the vicinity of the VWFA, or prosopagnosia, following a right hemisphere lesion to the vicinity of the FFA. We predicted that, if the cortical systems mediating face and word recognition are distributed across both hemispheres and are not independent, then we would expect to see co-mingling of the deficits. Specifically, pure alexic patients should have some measure of face recognition impairment along with their alexia, and prosopagnosic patients should have some measure of word recognition impairment along with their face recognition difficulty. Given the well-established hemispheric superiority for words in the left and faces in the right hemispheres, however, the impairment in the "preferred domain" (words in left and faces in right) should be greater than in the nonpreferred domain; thus, the pure alexics should be more impaired at word than face recognition, and the prosopagnosics should show the converse, and both patient groups should be impaired, even in the nonpreferred stimulus domain, relative to controls.

Materials and Methods

Participants

Two groups of patients participated in this study, the first comprised of 4 individuals with pure alexia and the second comprised of 3 individuals with prosopagnosia. Every patient had damage to only 1 hemisphere (left for pure alexics, right for prosopagnosics), with the opposite hemisphere structurally intact. Matched control participants were also recruited. All participants had normal or corrected-to-normal vision, were right handed and gave informed consent. The protocol was approved by the IRB of Carnegie Mellon University.

All 7 individuals performed within age-matched norm limits on finger-tapping speed (score computed for each hand separately as mean of 5 trials of 10 s per trial; see Strauss et al. 2006). As a means of ensuring that any differences that might be evident between the controls and the patients (or between the patient groups) are not attributable to a general visual processing impairment, patients completed the spatial subtests (dot counting, position discrimination, number location, and cube analysis) of the visual object and space perception battery (VOSP; Warrington and James 1991) and all performed within the normal range on these measures, using the criteria cutoffs provided by the test norms. In addition, a subset of the patients (2 prosopagnosic, 2 alexic) completed a computerized version of the Benton Line Orientation test (Benton et al. 1983) (see Supplementary Material, for an example, of stimulus display and for details of procedure and results). In this experiment, participants were shown 2 oriented lines at the top of the screen (drawn from a set of 11 possible lines, each varying by 15°). Below these 2 "probe" lines, a black horizontal bar appeared and below that, all 11 lines were displayed with a number adjacent to each line. The display appeared for unlimited exposure duration. Participants were required to type on the keyboard the numbers associated with the 2 probe lines, and reaction time (RT) and accuracy were recorded. There was no group difference between patients and controls in performance in either accuracy or RT, and no individual patient's score fell outside the distribution of the control group (determined by modified *t*-test, Crawford and Garthwaite 2004). These findings rule out any a priori deficit in general visuospatial processing and license us to explore the word and face recognition skills of the patients in detail.

Pure Alexia Group (Alexia)

All 4 patients (3 males) were premorbidly normal readers and none reported obvious problems in face recognition. A single axial slice from a structural MRI scan for each patient is shown in Figure 1 (top row) and, consistent with existing accounts of the disorder, all sustained damage unilaterally to the left inferior temporo-occipital lobe. Importantly, the right hemisphere is structurally intact in all cases. All patients were able to identify letters, as determined by their high accuracy in identifying a single letter, drawn randomly from the alphabet, presented in the center of a computer screen for 50-ms duration. Three of the 4 patients exhibited a field defect of some type (see below). Details for each case are provided next.

DK, a 75-year-old male, suffered a left posterior cerebral artery infarction in 1995 (see Fig. 1, top row). He completed 10th grade and worked in a grocery shop post stroke. DK suffered from a right homonymous hemianopia at the time of this testing and was diagnosed as a letter-by-letter reader in previous research investigations (Behrmann, Nelson et al. 1998; Behrmann, Plaut et al. 1998).

EL is a 56-year-old female with a history of mitral valve prolapse. In April 1996, she was admitted to hospital after suffering 2 embolic events that caused blurred vision, right arm weakness, and slurred speech. Her speech and language difficulties and the arm weakness recovered rapidly. EL was diagnosed as having bacterial endocarditis. A 2009 3T MRI scan reveals a left posterior cerebral artery infarct (see Fig. 1, top row). EL suffers from a right upper quadrantanopsia with macular sparing. EL was a reading teacher for dyslexic children. EL was diagnosed previously as a letter-by-letter reader (Behrmann, Nelson et al. 1998; Montant and Behrmann 2001; McKeeff and Behrmann 2004).

FF, an 84-year-old financial analyst suffered a left posterior hemorrhage in 2003, affecting primarily temporal cortex with slight incursion into the parietal lobe (see Fig. 1, top row). Following this, he was diagnosed with pure alexia, with some anomia but no frank aphasia. Past medical history was unremarkable, and he received rehabilitation for the reading disorder.

SH is a 64-year-old attorney with a past medical history of proximal atrial fibrillation and hypertension. In July 2004, he experienced a sudden onset of right-sided vision loss, dizziness, and headache, and was hospitalized with a right homonymous hemianopsia. A 1.5 T MRI revealed a left thalamus and left occipitotemporal lesion compatible with a left PCA infarct (see Fig. 1, top row).

Prosopagnosia Group (Prosop)

The 3 patients (all male) were premorbidly normal readers, by self-report, and none complained of a reading impairment. A single axial slice from a MRI scan is shown for each patient in the bottom row in Figure 1, and, as evident, all 3 suffered damage to the right inferior temporo-occipital lobe. The lesion site is compatible both with previous studies of prosopagnosia (Barton 2008) and with the existing findings of face-selectivity regions as revealed by fMRI (see above). All patients had a structurally intact left hemisphere and full visual fields, and all were unimpaired at single letter identification, evaluated in the same way as for the pure alexic patients described above.

SM sustained a closed head injury in a motor vehicle accident at the age of 18. A 3 T MRI scan from 2009 indicated a circumscribed lesion in right occipito-posterior temporal cortex in the vicinity of area LOC (see Fig. 1, bottom row; for detailed lesion demarcation, see (Konen et al. 2011)). SM's prosopagnosia is indicated by his impaired performance in the Benton Facial Recognition Test (32/54; normal 41–54). He is unable to recognize pictures of any famous people, despite being able to provide a good verbal identification when presented with their names auditorily. Further details of his medical and neuropsychological history are available in other publications (Gauthier, Behrmann et al. 1999; Marotta et al. 2001; Behrmann and Kimchi 2003; Nishimura et al. 2010; Konen et al. 2011).

RN is a 52-year-old right-handed male who suffered a stroke following a myocardial infarction in May 1998. His most recent 3 T MR scan (Fig. 1, bottom row) revealed several gross abnormalities (enlarged ventricles, widespread atrophy) and dense inhomogeneities in the right occipitotemporal area. RN performed at the borderline level on the Benton Face Recognition test (score 40/54) and recognized only 4 of a set of 50 difficult famous faces (his wife, who served as a control, recognized 14 faces) (Humphreys et al. 2007). Further biographical and performance details are available from other studies in which RN has participated (Marotta et al. 2002; Behrmann and Kimchi 2003).

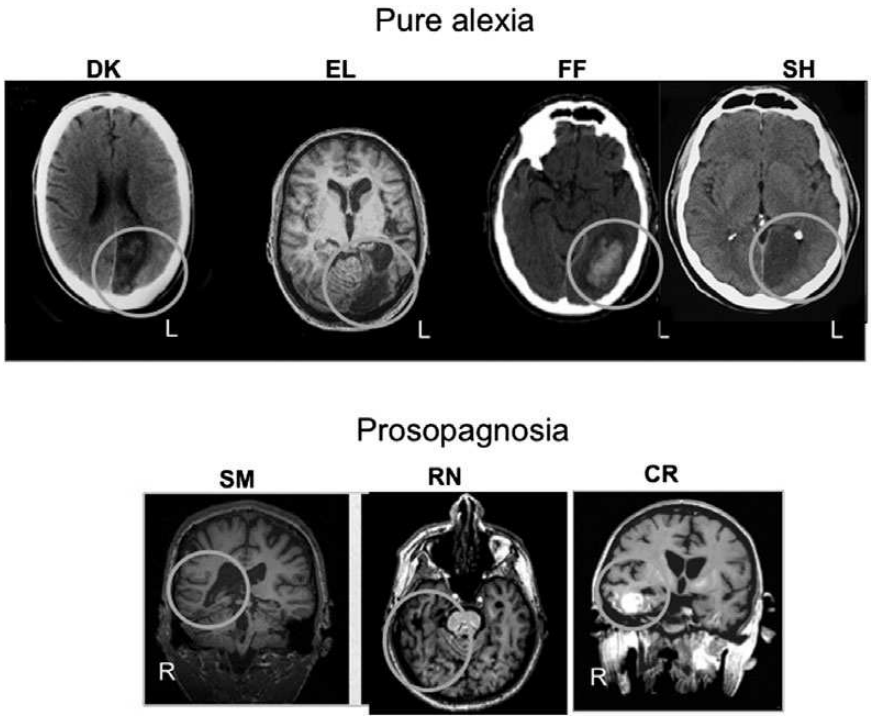

Figure 1. Representative axial slice from the MRI scan (1.5 or 3 T) of each of the 4 patients with pure alexia, all showing left occipitotemporal lobe involvement (top row) and a representative slice from the MRI scan of each of the prosopagnosic patients. Details regarding etiology of lesion and time since onset may be found in Methods section.

CR is a 31-year-old right-handed male who suffered from a right temporal lobe abscess with a complicated medical course including a history of Group A toxic shock syndrome, pneumonia, cardiac arrest, candida bacteremia, and metabolic encephalopathy in May 1996. MR scans (3 T) reveal a lesion consistent with acute microabscesses of the right temporal lobe and medial occipital lobe (see Fig. 1, bottom row). CR has other punctate lesions in the right hemisphere (petechial hemorrhage observable along the gray/white junction) but the left hemisphere is unaffected. CR has full visual fields but his performance is in the "severely impaired" range on the Benton Facial Recognition tests (scores of 36/54), and he is unable to recognize pictures of any famous people (e.g., Bill Clinton). CR has participated in previous studies (Gauthier, Behrmann et al. 1999; Marotta, Genovese et al. 2001; Behrmann and Williams 2007; Humphreys et al. 2007).

Although a clearer analysis of the lesion site of patients with pure alexia and with prosopagnosia would be useful, we were unable to do this—most of our patients had clinical scans acquired under different conditions (different scanners, different intensity values), precluding a thorough analysis of the lesion site and size. Doing so in future studies, however, would be valuable in confirming the topography of the lesions.

Some of the findings discussed here on the face processing abilities of a subset of these prosopagnosic individuals have been previously reported (Marotta et al. 2002).

Control Participants

Control participants, recruited from the volunteer pool at the Osher Life Long Learning Institute at Carnegie Mellon University, or from the academic and neighboring community, were matched to the Alexia and Prosop participants. Two controls matched each patient on age, gender, and educational background. The participants were native English speakers with no history of neurological disease or of reading or face recognition difficulties. The controls for the Alexia patients were 6 males and 2 females, aged 51–75 years with a mean age of 64.6 years. The controls for the Prosop patients were 6 male individuals, aged 27–54 years, with a mean age of 37.2 years.

Apparatus and Procedure

A Dell laptop with a 15″ display, running *E*-Prime, was used for all experiments. Verbal response times were taken via a desktop microphone and the PST Serial Response Box, and manual responses were taken from the keyboard. Accuracy and RT were recorded for all studies. Participants were seated ~50 cm from the screen for all experiments.

Analysis Procedure

We first compare data from the 2 patient groups against their respective control groups to establish whether any impairment is present, and then against each other, to assess the severity of any observed impairment. We do not compare the Alexia patients to the Prosop controls nor the Prosop to the Alexia controls. While, in principle, we expect the 2 control groups to perform equivalently well on all experiments, given the difference in age (Alexic controls older than Prosop controls), we anticipated some slowing in RT in the Alexic controls compared with the Prosop controls. We therefore provide the comparison of the 2 control groups in every experiment, as well.

We summarize the results of all pairwise patient group comparisons in Table 1. We also compare each patient against his/her own controls using the modified *t*-test for examining a single patient data point (Crawford and Garthwaite 2004), and the outcomes of these single case comparisons are shown in Table 2. Because of the large number of potential *t*-test comparisons for each single case (each cell in each experiment), we select only the most informative comparison or summary statistic for the comparisons. Bonferroni familywise correction is employed for multiple comparisons, as necessary.

Experiment 1: Word Processing

Two experiments were conducted, one requiring the reading aloud of words and the other requiring lexical decision.

Table 1
Summary of ANOVA outcomes for patients versus controls and patient group comparisons

	Pairwise group comparison of patients vs. controls and of Alex vs. prosop		
Experiment and dependent measure	Alex vs. controls	Prosop vs. controls	Alex vs. prosop
Word reading			
Accuracy	Main effect group; interact with length	Main effect group	No significant difference
RT	Main effect group; interact with length	Main effect group; interact with length	Main effect group; interact with length
Lexical decision			
Accuracy	Main effect group; Interact with length	No significant difference	No significant difference
RT	3-way interaction: group × length × string type	Main effect group; interact with length	No significant difference
Simultaneous face discrimination			
Accuracy (3 levels)	Main effect group	Main effect group	No significant difference
Accuracy (2 levels)	Main effect group	Main effect group	Interaction of group × difficulty
Face-matching orientation effects			
Accuracy	No significant difference	Main effect group; interact with orientation	Main effect of group; interaction with orientation
RT	Main effect group; interact with orientation	Main effect group; interact with orientation	Interaction of group × orientation
Rotation			
Accuracy	Main effect of group; interact with target rotation	Main effect of group	Main effect of group; interact with target rotation
RT	Main effect of group; interact with target rotation	Main effect of group; interact with target rotation	No significant difference

Experiment 1a: Word Reading

Methods

Stimuli. A single word appeared centered over fixation for unlimited duration, and the participants were required to read it aloud as fast and as accurately or possible. Note that for the Alexia patients with field defects and no macular sparing (DK and SH), and their matched controls, the stimuli were presented to the left visual field with the final letter of the word placed immediately adjacent to fixation. All words were presented in uppercase Geneva 24-point bold font in black on a white background. To assess the effect of word length on RT, 60 words, 20 each of 3, 5, and 7 letters, were included. Words subtended visual angles of ~0.5° vertically and ~1.5°, 2.4°, and 3.6° horizontally for the 3 word lengths, respectively. Word frequency was controlled, with an equal number of high- (>20 times per million) and low-frequency (<20 times per million) words per word length (Kucera and Francis 1967). The words had a mean word frequency of 52 (SD = 70), with half abstract and half concrete words. This word list has been used previously with alexic patients (Behrmann et al. 1990; Behrmann and McLeod 1995; Behrmann and Shallice 1995).

Procedure. Subjects were instructed to read aloud each word as quickly and as accurately as possible. The words were shown individually, with length randomly intermixed in the block of trials. On each trial, a fixation point appeared for 1000 ms after which the target word appeared and remained visible until the subject activated the vocal response key by reading the stimulus aloud. An interval of 2 s occurred between trials. RT was recorded using a voice key and the experimenter noted any errors. Participants practiced on a short list of words, none of which appeared on the subsequent experimental lists. Trials on which the microphone was mistriggered were removed from the analysis.

Table 2
Single case summary statistics (patient vs. matched controls)

Experiments	Pure alexia				Prosopagnosia		
	DK[a]	EL	FF	SH[a]	SM	RN	CR
Word reading (RT slope)	**	**	**	**	*	**	**
Lexical decision (RT slope words)	**	**	**	*	**	**	*
Face discrimination (error in "easy" condition)	ns	*	*	ns	**	*	**
Face discrimination (error in "medium" condition)	*	*	**	**	**	**	**
Face orientation (Inverted RT–upright RT difference)	*	**	**	**	**	**	*
Face rotation (accuracy in profile view)	*	**	**	*	**	**	**

Note: [a]Hemianopia.
*$P \leq 0.05$.
**$P < 0.01$.

Results and Discussion

Repeated measures ANOVAs were performed with group as the between-subjects factor, and word length as the within-subjects factor. Analyses are conducted first with accuracy and then with RT as the dependent measure. Given the interest in the group differences, throughout, only main effects of group and factors that interact with group are reported. Note that a direct comparison of the 2 control groups reveals no main effects of group or any interactions with group and this is true for both accuracy and RT.

Accuracy

The Alexia group made significantly more errors than its control group, ($F_{1,10} = 117.6$, $P < 0.001$) (mean errors: Alexia 4.4, Controls 0.3), especially as word length increased, ($F_{2,20} = 3.4$, $P = 0.05$). The Prosop group also made significantly more errors than its control group ($F_{1,7} = 6.8$, $P < 0.05$)

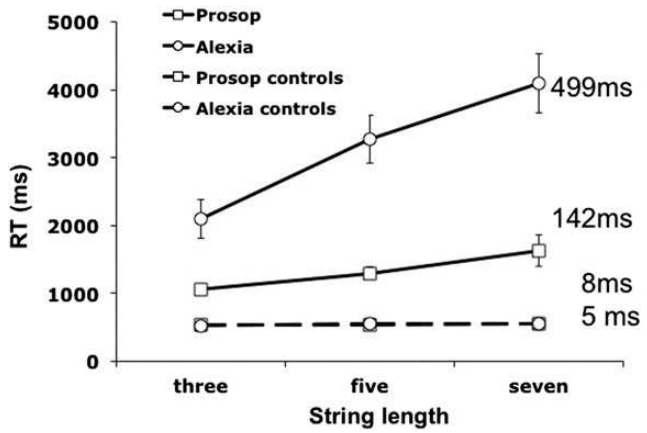

Figure 2. Mean RT [and 1 standard error (SE)] for Prosop and for Alexia groups, as well as for each of their matched control groups, as a function of word length, for single word reading. The slope, calculated by regressing RT against word length, is included for each group.

(mean errors: Prosop 2.2, Controls 0.27) but this did not interact with word length. There was no significant difference between the Alexia and Prosop groups in the number of errors, and there was no interaction of group × length (both $F < 1$).

RT

The data from the 2 patient groups, and their control groups are shown in Figure 2 (note that the data from the 2 control groups overlap confirming the similarities in performance). The Alexia group was significantly slower than its control group, ($F_{1,10} = 36.5$, $P < 0.001$), especially as word length increased, ($F_{2,20} = 52.8$, $P < 0.001$). The Prosop group was slower than its matched controls ($F_{1,7} = 120.4$, $P < 0.001$), especially as length increased, ($F_{2.14} = 67.8$, $P < 0.001$). Of note, the Alexia group performed more slowly than the Prosop group, ($F_{2,10} = 6.7$, $P = 0.04$), and disproportionately so as word length increased, ($F_{1,5} = 8.96$, $P < 0.001$). The contrasts between the 2 patient groups, and their controls is clearly evident in the slopes, calculated by regressing RT against word length: whereas the controls for the Alexia and Prosop groups evinced slopes of 5 and 8 ms per additional letter, respectively, the Prosop patients required 142 ms per additional letter, and the Alexia patients required almost 4 times longer, with a slope of 499 ms per letter.

Single Case Comparisons

The data from each individual patient were compared directly against his/her own matched controls (see Table 2). Here, we examined the slope in RT across word length (as a summary index) and all 7 patients had statistically steeper slopes than their controls, although the Prosop participant, SM, was slightly less affected than the others.

Experiment 1b: Lexical Decision

To confirm that the group differences observed above held independent of the requirement for overt articulation of a response, this experiment did not require participants to produce a verbal response.

Methods

Stimuli. The words from the word-reading task were combined with 60 nonwords, which were created by changing 1 or 2 letters of the real words. All nonwords were pronounceable and orthographically legal; for half the nonwords, the divergence from a real word occurred in the first half of the word whereas the converse was true for the other nonwords. This experiment was run in a separate session from the word-reading task.

Procedure. Following a fixation point that appeared for 1 s, a letter string was presented centrally and remained visible until a keypress was made (again with half-field presentation for the 2 hemianopic alexics and their controls). The intertrial interval was 1 s. Subjects decided whether or not the string was a real English word and responded by pressing 1 of 2 keys using 2 fingers of their dominant (right) hand for a "yes" or "no" response. The keys were counterbalanced across subjects. Subjects performed practice trials and were instructed to complete the task as quickly as possible without sacrificing accuracy. Accuracy and RT were both analyzed. We also analyzed performance using d' as the dependent variable (note that we assume hit rate = 0.999 and false alarm rate = 0.001 in cases where these are 1.0 and 0.0, as is true for some control participants).

Results and Discussion

An ANOVA with string length (3, 5, 7) and type (word, nonword) as within-subjects factors and group as a between-subjects factor was conducted with accuracy, d' and RT as the dependent measure. Note that a direct comparison of the 2 control groups with string length and type as within-subjects factors revealed a main effect of group ($F_{1,12} = 6.9$, $P = 0.02$), with the Alexic controls performing less accurately than the Prosop controls. The same finding held using RT as the dependent variable, ($F_{1,12} = 5.08$, $P = 0.04$) (see Fig. 3).

Accuracy

The Alexia group performed significantly less accurately than its control group, ($F_{1,10} = 11.6$, $P < 0.01$), especially as string length increased, ($F_{2,20} = 3.5$, $P < 0.05$), and no other effects or interactions were significant. The Prosop group's performance did not differ either from their matched controls or from the Alexia group on any factors (all $F < 1$).

d'

The Alexia group performed significantly less accurately than its control group, ($F_{1,10} = 27.6$, $P < 0.001$) although this did not vary across string length, ($F < 1$). The Prosop group's performance did not differ either from their matched controls or from the Alexia group on any factors (all $F < 1$).

RT

Mean RTs [and standard error (SE)], as a function of length, are plotted in Figure 3 for all groups. As evident from this figure, the Alexia group made lexical decisions significantly more slowly than its control counterpart, $F_{1,20} = 42.2$, $P < 0.001$), but this was qualified by an interaction with length, ($F_{2,20} = 17.4$, $P < 0.001$) and by a 3-way interaction of group × length × string type, ($F_{2,20} = 9.6$, $P < 0.001$). As revealed by post hoc Tukey tests ($P < 0.05$), the 3-way interaction emerged because the disproportionate increase in RT with string length was greater for nonwords than for words in the Alexia group, relative to the controls. The Prosop group made lexical decisions more slowly than its matched control ($F_{1,10} = 67.4$, $P < 0.001$), and this too was qualified by an interaction with length ($F_{2,20} = 23.5$, $P < 0.001$) but this did not interact with string type. The Alexia and Prosop group did not differ significantly in their RT, and no interactions were significant (all $F < 1$). With regard to the slopes of these RT-length functions, as evident from Figure 3, there was a, minimal, if any, change in slope across string length for words and nonwords for the 2 control groups. There was a moderate cost in RT across length for the Prosop group (slopes 159 and 178 ms for words and nonwords) but the slope for the Alexia group was roughly 2 to 3 times this for words (342 ms) and far greater for nonwords (639 ms).

Single Case Comparisons

The single-subject comparisons for the lexical decision task compared the slope (across string length for words only) for each patient and his/her matched controls. All patients had

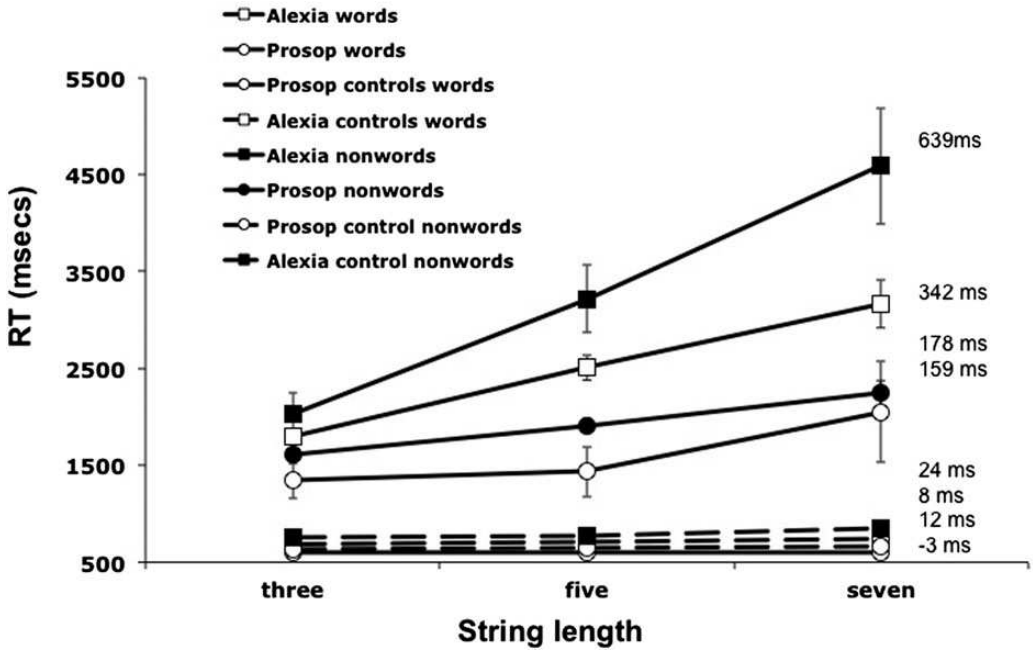

Figure 3. Mean RT (and 1 SE) for Prosop and for Alexia groups, as well as for each of their matched control groups, as a function of string type and length, for lexical decision. The slope, calculated by regressing RT against string length, is included for each group and for words/nonwords.

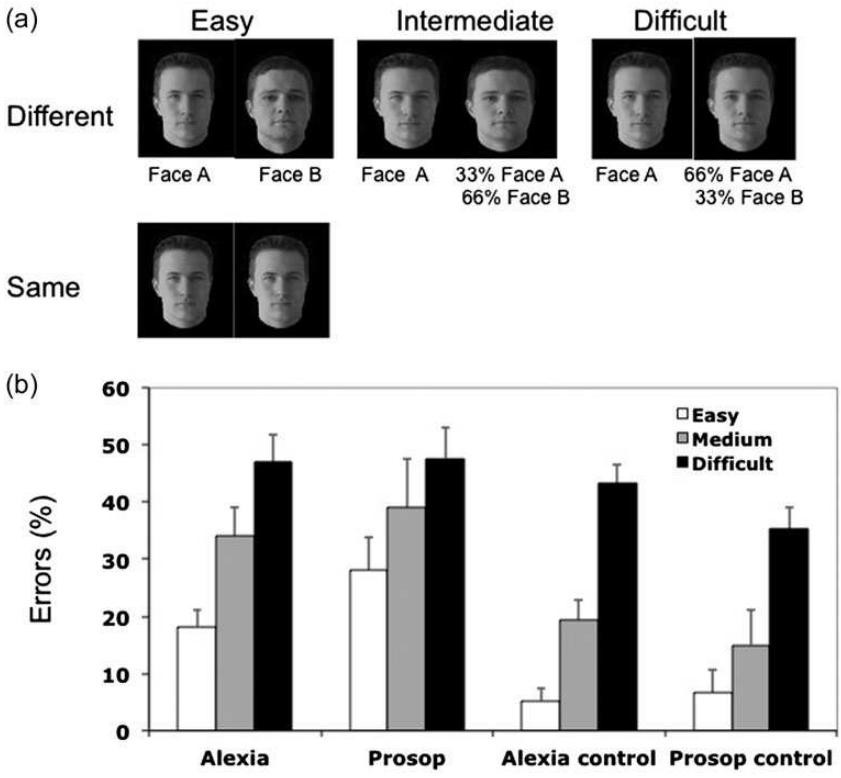

Figure 4. (*a*) Examples of stimuli from the easy, medium, and difficult different conditions, and from the same condition. (*b*) Mean % error rate (and 1 SE) for the Prosop and Alexia groups and for their matched control groups for each different condition.

significantly steeper slopes than the controls, with SH (Alexia) and CR (Prosop) less affected, relative to their own controls ($P < 0.05$), than the other patients.

Taken together, the findings from the word reading and lexical decision tasks confirm that the Alexia patients, all of whom have left occipitotemporal lesions, fit the typical profile of pure alexia: they were slower than their controls, and the increase in RT across word length was disproportionately steep. The Alexia patients also made significantly more errors than their controls, especially toward the ends of words, for

example, "trust" for "truck," and "recite" for "recital, and this increased as word length increased. The Alexia patients were also disproportionately slowed, as a function of string length, relative to the Prosop patients, although this was evident only in word reading, and the number of errors across the 2 groups did not differ on either task. The novel and most interesting result is that the Prosop patients, all of whom have lesions to the occipitotemporal region of the right hemisphere, were not normal in their orthographic processing abilities, and were significantly slowed in their reading, relative to their own controls. Like the Alexia patients, they were disproportionately slowed as string length increased in both word reading and lexical decision.

The case study comparisons support the group findings—the Alexia and Prosop patients read aloud and made lexical decisions significantly more poorly than their controls, and this was true for each of the individual cases, as well, including the right hemisphere Prosop patients.

Experiment 2: Face Recognition

Experiment 1 revealed that, relative to controls, both the Alexia and Prosop groups were impaired on word recognition. Experiment 2 explored the complement of this finding and evaluated the face recognition performance of the patient groups and controls.

Experiment 2a: Simultaneous Face Discrimination

In this first face experiment, we documented the speed and accuracy with which the Alexia and Prosop groups and their control groups discriminated between a pair of novel faces. Importantly, we manipulated the difficulty of the discriminability between the faces in the pair and assessed the differential impact of this manipulation. This methodology has been used successfully to examine face discrimination as a function of age (Thomas et al. 2008).

Methods

Stimuli. Two novel faces were presented in gray scale side-by-side on either side of the fixation point (Fig. 4*a*) (for the hemianopic Alexia patients and their controls, the faces were presented entirely to the left of fixation). The faces in the pair could be either identical (25% of trials; $N = 55$) or different (75%; $N = 165$). The different trials could be drawn from Easy, Medium or Difficult conditions ($N = 55$ in each of these levels of difficulty). The Easy condition consisted of a display of 2 different faces (e.g., Face A and Face B). For the medium and difficult trials, the 2 faces (say Face A and Face B) were morphed together using the MorphMan 4.0 software. For the medium condition, Face A was presented with a second face that was a morph comprising 33% of Face A and 66% of Face B, while in the difficult condition, Face A was presented with a second face that was a morph comprising 66% of Face A and 33% of Face B. Each stimulus was roughly 2×3 in. and the midpoint of each stimulus was located 5.2 inches from the fixation point (see Thomas et al. 2008 for more details). Although the proportion of same and different trials were unbalanced (potentially leading to a response bias), we elected to do this so we could sample mostly different trials.

Procedure. Each display was presented for unlimited exposure duration. Participants were informed that, on each trial, 2 faces would appear, and they were to decide whether the faces were the same or not and to indicate their response using 1 of 2 keys on the keyboard ("D" or "S") as accurately and as quickly as possible. Condition (same, different—easy, medium, difficult) was randomized within a block.

Results and Discussion

An initial comparison of the 2 control groups against each other with condition (easy, medium, difficult) as the within-subject factor revealed no main effect of group nor an interaction with level of difficulty in either accuracy or RT.

Accuracy

As evident in Figure 4*b* and summarized in Table 1, the Prosop group made significantly more errors than their controls, ($F_{1,7} = 8.2$, $P < 0.05$) and the same was true for the Alexia group relative to their controls, ($F_{1,10} = 5.8$, $P < 0.05$). There was no difference in overall accuracy level between the 2 patient groups ($F < 1$). No interactions with difficulty level were observed in any of these ANOVAs presumably because performance in the "difficult" condition was at or approached chance level for all 4 groups. To circumvent this floor effect, we reran the group analyses using only the "easy" and "medium" conditions.

In ANOVA with just the easy and medium levels, there was still a main effect of group for the Prosop versus Controls, ($F_{1,7} = 7.1$, $P < 0.05$) and for the Alexia versus Controls, ($F_{1,10} = 8.8$, $P = 0.01$). There was no difference in accuracy between the 2 patient groups, but there was a significant interaction of patient group × condition, ($F_{1,5} = 22.1$, $P < 0.005$). This interaction arose because the groups were equally inaccurate in the medium condition but the Prosop group was less accurate than the Alexia group in the easy condition. Thus, even when the discriminations were fairly easy, the Prosop group performed poorly but, the impairment in the Alexia group was evident only when the faces were somewhat more similar and harder to differentiate (This same pattern of findings held when we computed an inverse efficiency score (RT/accuracy) indicating that the difference between the Prosop and Alexia group is not a consequence of a speed-accuracy trade-off (significant interaction of patient group × condition, [$F_{1,5} = 13.2$, $P < 0.01$]).

Although the manipulation of interest was accuracy as face discrimination increased in difficulty (i.e., the different trials), we also analyzed the accuracy from the same trials but in a separate analysis. With accuracy for same trials as the dependent measure, there was still a main effect of group for the Prosop versus Controls, ($F_{1,7} = 39.8$, $P < 0.001$) and for the Alexia versus Controls, ($F_{1,10} = 9.7$, $P < 0.01$). There was no difference in accuracy between the 2 patient groups, ($F_{1,5} = 0.12$, $F > 0.7$).

In light of the fact that the error rates were so high for the difficult condition but also to some extent for the other conditions, we did not analyze the RT data.

Single Subject Comparison

In these comparisons, we examined the error rate for the patient versus matched control in the "easy" and "medium" condition. All of the Prosop patients performed significantly

more poorly than their controls and 2 of the Alexia patients performed significantly less accurately than their matched controls.

Experiment 2b: Inversion and Depth Rotation in Face Matching

Having shown that both the Prosop and Alexia groups performed more poorly than their controls (and Prosop more poorly than Alexia in the easy condition), we compared the groups under 2 well-established and more telling manipulations of face perception: when the faces were presented upright versus inverted in the image plane, and when the faces to be matched were upright but rotated in depth differently.

The upright versus inverted comparison in the 2 patient groups is of great interest as it has been suggested that prosopagnosic individuals, relative to controls, show an inversion superiority effect, performing better with inverted than upright faces (Farah et al. 1995, 1998) or, at least, not showing the normal inversion inferiority effect (i.e., equivalent performance for upright and inverted faces) (Avidan et al. 2011; Busigny and Rossion 2010, 2011). This atypical pattern is usually attributed to impairment in holistic processing in prosopagnosia (Levine and Calvanio 1989; Barton et al. 2002; Barton 2009), which reduces the ability to extract the configural representation of the face as is standardly done with upright faces. Because inverted faces do not tap into this configural representation and are thought to be processed in a more part-based fashion, the prosopagnosics do relatively better with the inverted than with the upright faces. Examining whether a similar pattern holds for the Alexia group might shed light on the computations mediated by each hemisphere. Note that a distributed and graded account of face and word specialization does not deny hemispheric differences, but claims that the processing of both stimulus classes will exhibit, to different degrees, the characteristics of both hemispheres.

The assessment of performance across depth rotation also serves as a valuable probe of the mechanisms underlying face perception in the Alexia and Prosop groups. Others and we have previously established that prosopagnosic individuals perform poorly at matching faces across different degrees of rotation (e.g., Marotta et al. 2002). Examining this ability in the patients with pure alexia may help uncover similarities and differences in the profiles of the 2 patient groups in face perception performance.

Methods

Stimuli. The stimuli consisted of color pictures of male and female faces initially collected using a Cyberware™ 3D laser-scanner and collated in the Max-Planck Face Database. This database consists of a series of 3D models of real faces in 3 rotations in depth around the vertical axis—full-frontal face (0°), right three-quarter (45°), and right profile (90°) (see Fig. 5*a–c*, e.g., of the 3 degrees of rotation). Hair was covered, leaving only the face image. 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.

Procedure

On each trial, 3 stimuli appeared on a gray background: a target face (centered over fixation, 5.5 cm from the top of the screen) and 2 choice faces, 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. 5*d*,*e*). The 2 Alexia patients with field defects, and their matched controls, saw all stimuli in the intact left field (although there was unlimited exposure duration, and they were free to move their eyes, we still opted for left field presentation to avoid any adverse effect of the hemianopia). Each trial began with a fixation cross appearing for 250 ms, followed by the 3 stimuli, which remained on the screen until response. In the first part of the study, only upright faces, varying within and across rotation, were shown (see example in Fig. 5*d*). The target could appear in 1 of 3 possible rotations (frontal, three-quarter and profile) and this was true of the choices too, resulting in 9 possible target face × choice faces rotation combinations. Note that, on any one trial, the 2 choice faces were always rotated to the same angle within a trial, for example, both might be 45°, as shown in Figure 5*d*. The 9 conditions were randomly mixed within each block of trials, with 40 trials per cell for a total of 360 trials. Trials were divided into 2 blocks with a short break between them. Participants pressed a left or right key to indicate the side of the match to target.

Once this rotation study was complete, participants completed an additional block of trials, in which the target was always upright, and on half the trials, the choices were both upright, whereas in the remaining half, the choices were both inverted. The target and choice faces were only ever shown in the frontal view (see Fig. 5e). Participants pressed a left or right key to indicate the side of the match. Again, there were 40 trials per cell (inverted/upright) for a total of 80 trials.

Results and Discussion

We describe the effect of image-plane inversion on performance first and then present the depth rotation results.

Upright versus Inverted

A direct comparison of the 2 control groups with orientation (upright/inverted) as the within-subject factor reveals no effects with accuracy as the dependent measure. With RT, the Alexic controls performed significantly more slowly than the Prosop controls, ($F_{1,12} = 12.3$, $P < 0.005$) but there were no interactions with stimulus orientation.

Accuracy

As shown in Figure 6*a*, the Prosop group made significantly more errors than their matched controls, ($F_{1,7} = 62.8$, $P < 0.001$), with disproportionately more errors for upright than inverted faces, as revealed by the group × orientation interaction ($F_{1,7} = 9.3$, $P = 0.01$). There were no differences in accuracy between the Alexia group and its controls. Lastly, the Prosop group made more errors than the Alexia group, ($F_{1,5} = 23.5$, $P < 0.005$) and the interaction of group × orientation condition was marginally significant, ($F_{1,5} = 5.8$, $P = 0.06$), with more errors for upright than inverted faces in the Prosop group and no difference across orientation for the Alexia group.

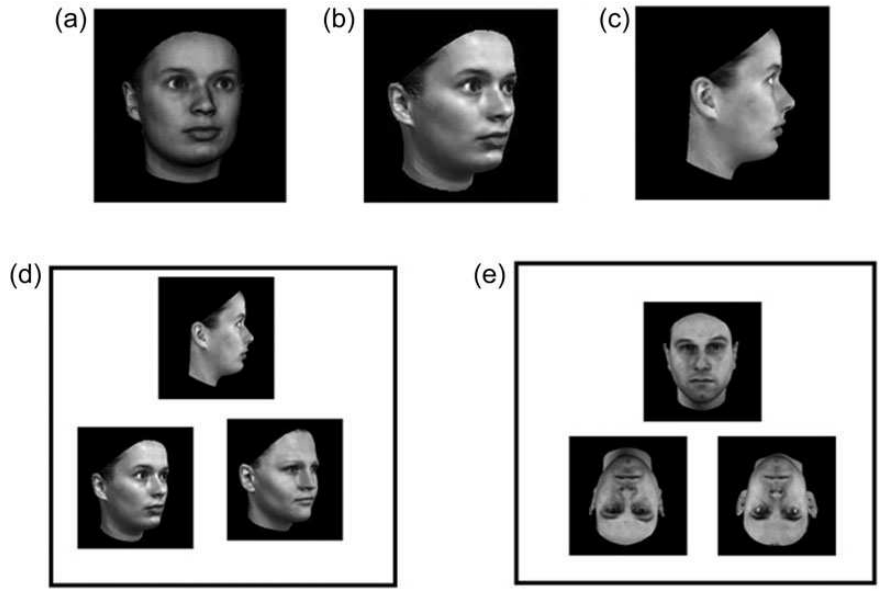

Figure 5. (*a–c*) Example of a single-face stimulus presented in frontal, three-quarter, and profile view. (*d*) Example of an upright trial with the target at the top and the 2 choices at the bottom; the choice on the left is the correct match. Note that the choices always share the same degree of rotation and, here, differ from the degree of rotation of the target. (*e*) Example of an inverted trial with the target at the top and the 2 choices at the bottom; the choice on the left is the correct match. Note that the target was always presented upright.

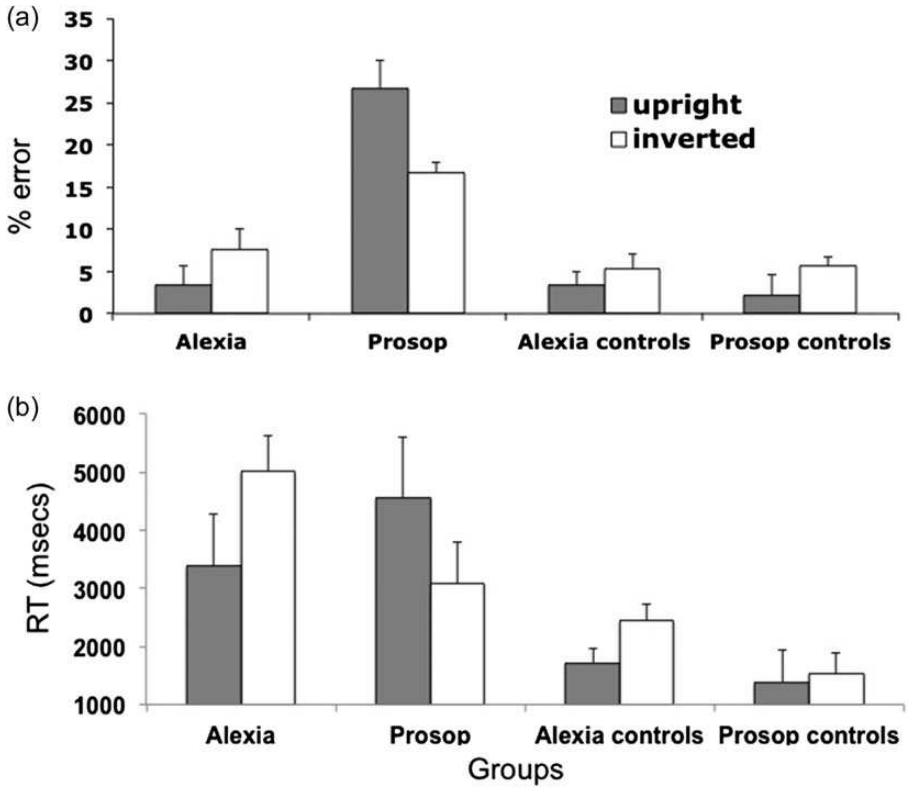

Figure 6. (*a*) Mean % error (and 1 SE) and (*b*) mean RT (and 1 SE) for Alexia and Prosop groups and for their matched control groups for upright and inverted face matching.

RT

The Prosop group performed significantly more slowly than the controls, ($F_{1,7} = 10.1$, $P = 0.01$), although this varied as a function of orientation, ($F_{1,7} = 6.8$, $P < 0.04$). As seen in Figure 6*b*, the Prosop controls showed a slight, albeit nonsignificant, increase in RT for inverted over upright faces but the Prosop group showed faster RTs on inverted than upright faces ($P < 0.05$), which mirrors their accuracy data. The Alexia group also performed significantly more slowly than their matched controls, ($F_{1,10} = 24.9$, $P = 0.001$), and this

too was qualified in an interaction with orientation, ($F_{1,10} = 4.8$, $P = 0.05$): unlike the Prosop group, however, the Alexia group showed the same pattern as the controls—that is, the Alexia patients were slower at inverted than upright trials albeit to a greater degree than their controls. Finally, there was no main effect of group between the Prosop and Alexia, but there was a significant interaction of group × orientation, ($F_{1,5} = 21.5$, $P < 0.01$). Whereas the Prosop group revealed significantly faster RTs for inverted than for upright, the opposite was true in the Alexia group. The interesting and novel finding was that despite the slowed RTs of the Alexia patients, they continued to evince the advantage for the upright over inverted faces and this contrasts with the inversion superiority seen in the Prosop patients.

Single Subject Comparisons

For these analyses, we derived a difference measure (inverted RT—upright RT) for each individual and performed the comparison against the matched controls. All 7 patients performed more slowly than their controls—each of the Alexia patients (to a lesser degree for DK) was differentially slower than controls, with greater slowing on inverted than upright, whereas for the Prosop patients (to a lesser degree for CR), the reverse was true.

Matching Across Depth Rotation

An ANOVA was performed with 2 within-subject factors: target rotation (frontal, profile, and three-quarter) and match rotation (frontal, profile, and three-quarter). An initial comparison of the 2 control groups against each other with target rotation and match rotation as the 2 within-subject factors revealed no group differences whatsoever in either accuracy or RT.

Accuracy

As evident in Figure 7*a*, the Prosop group made significantly more errors than its controls, ($F_{1,7} = 75.7$, $P < 0.001$), although this differed as a function of target viewpoint, ($F_{2,14} = 6.5$, $P = 0.01$): whereas the controls were most accurate on the three-quarter viewpoint (Bruce et al. 1987; O'Toole et al. 1998), this was not true for the Prosop patients. The Alexia group was as accurate as the matched controls ($F < 1$). The Prosop group was significantly less accurate overall than the Alexia group, ($F_{1,5} = 52.3$, $P < 0.001$).

RT

As shown in Figure 7*b*, the Prosop group responded significantly more slowly than the controls, ($F_{1,7} = 5.5$, $P = 0.05$), but this varied depending on the target viewpoint, ($F_{2,14} = 4.7$, $P < 0.05$): whereas both groups were faster on the three-quarter view relative to the other conditions, this advantage was greater for the Prosop group than the control group presumably because there was greater opportunity for a larger separation in RT between conditions given their slower performance (note also that because of the high error rate for the Prosop patients, the RT data may be somewhat unreliable). The Alexia group also performed more slowly than its control, ($F_{1,10} = 22.6$, <0.001), and this too was qualified by target viewpoint, $F_{2,20} = 3.3$, $P = 0.05$) in the same way as for the Prosop group: there was relatively faster performance for the three-quarter view than the other views in the Alexia group than was true in the controls. There was no significant difference between the Prosop and Alexia groups in overall RT, and, intriguingly, there was no interaction with any other variable indicating the same profile as a function of viewpoint (as can be seen in Fig. 7b). Finally, across all these analyses, the degree of rotation of the choices did not influence performance in any of these comparisons, and only the view of the target affected performance differentially.

Single Subject Comparison

The single-case analyses were done on the accuracy scores from the profile view—we chose this particular data point both because the Prosop patients were least accurate on this condition and because, as a result of this large error rate, an RT analysis was not feasible. As evident from Table 2, in this condition, all 3 Prosop patients performed more poorly than their matched controls and 2 of the 4 Alexia patients did, as well.

To sum up, we compared the performance of the 2 patients groups and their controls in matching faces across 2 manipulations, both of which are known to index competence in face perception: matching across frontal plane orientation differences (upright vs. inverted) and matching across depth rotation. In both accuracy and RT, the Prosops but not Alexia patients were less affected by inversion than their controls. The Alexia group was slower than the controls but the rank ordering of the orientations remained the same although the Alexia group showed greater separation between the conditions.

When considering the viewpoint data, both patient groups performed more slowly than the controls but the patterns were similar: relative to their controls, both groups were disproportionately slowed on the frontal and profile cases with relatively less slowing on the three-quarter views. The Prosop group made more errors than controls especially on the frontal and three-quarter trials, and more errors overall (but not qualified by viewpoint) than the Alexia group. The Alexia group and controls did not differ in accuracy. Single case comparisons largely supported these group findings.

General Discussion

The goal of this study was to examine whether the mechanisms supporting the recognition of visual words and faces are truly independent, as might be predicted on a domain-specific account, or are overlapping, as might be predicted on a more distributed and graded account. While it is clear that many neural areas and psychological processes are shared by face and word recognition (e.g., early visual cortex and regions engaged in eye movements), the crux of the argument concerns whether there are regions in ventral visual cortex selectively devoted to one or the other visual domain. In addition, to the extent that the mechanisms for faces and words are not independent, a further question is whether the neural system that mediates recognition of both of these classes is restricted to a single hemisphere or is instantiated across both hemispheres. To explore these questions, we conducted 2 series of experiments, one designed to characterize the word recognition abilities, and the other designed to characterize the face recognition abilities, of patients with pure alexia following a lesion restricted to the left hemisphere and of patients with prosopagnosia following a lesion restricted to the right

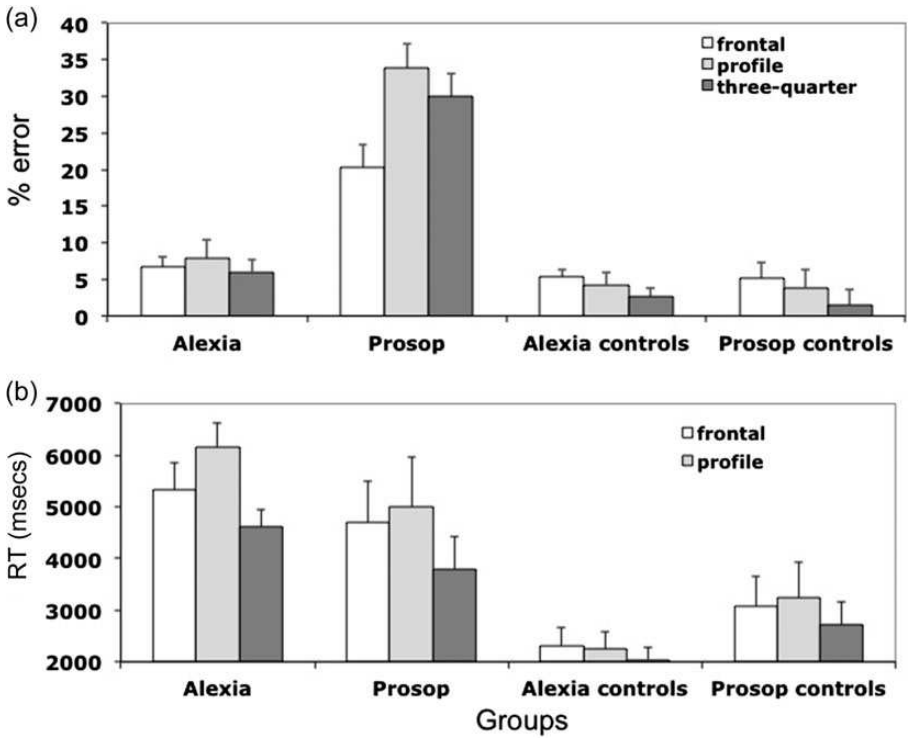

Figure 7. (*a*) Mean % error (and 1 SE) and (*b*) mean RT (and 1 SE) for Alexia and Prosop groups and for their matched control groups for matching faces as a function of degree of rotation (frontal, profile, and three-quarter views).

hemisphere. We compared the performance of these groups against each other and against matched controls and, for further analysis, compared each individual patient against his/her own matched controls.

The findings were straightforward: as expected, relative to controls, the pure alexic patients were impaired at word recognition in both speed and accuracy in reading aloud and in lexical decision. At the same time, the prosopagnosics were slower and less accurate in matching upright and inverted faces (and showed the so-called inversion superiority effect) and also made more errors and were slower when matching only upright faces that differed across viewpoint. We note that these group-level findings also held when the analysis was done at the single patient level.

While the patient groups were clearly impaired in the category traditionally associated with their side of lesion, the more telling question concerns their performance in the other category. Importantly, we observe deficits in both groups here too. The Alexia patients made more errors than their controls on discriminating morphed faces, and performed more slowly on matching upright and inverted faces. Unlike the Prosop patients, however, the Alexia patients showed the exaggeration of the normal upright superiority effect rather than the inversion superiority pattern.

In matching faces across rotation, the Alexia patients were as accurate as their controls but were slowed, especially for the more taxing frontal and profile views [the three-quarter view is considered easier as more featural information is available (O'Toole et al. 1998)]. The Alexia group made significantly fewer errors than the Prosop group on this task, and to a greater degree for profile and three-quarter views, but did not differ in RT. We also note that the individual Alexic patients all performed statistically more poorly on the selected indices for each task than their matched controls, with the exception of DK and SH who did not differ from their controls on the discrimination of morphed faces. In sum, across almost all analyses, the Alexia patients, as a group and as single cases, performed more poorly than their controls on all face tasks, although they were somewhat more accurate and not as slow in RT as the Prosop group.

The complement of this result held for the word recognition performance of the Prosop patients. The Prosop group made more errors than controls in word reading although not in lexical decision, and were slowed relative to the controls on both tasks, and disproportionately so as string length increased. There was no difference in error rate between the Prosop and Alexia groups on either word task. There was a substantially steeper slope for the Alexia than Prosop group on single word reading and although this slope difference did not reach statistical significance in lexical decision, there was a large numerical slope difference (Alexia 342 ms; Prosop 159 ms). All 3 Prosop patients behaved significantly differently from their matched controls on both word tasks.

Our analytic strategy has been to focus primarily on the comparison of the patients against their carefully selected matched controls and then to compare the patient groups to each other. It is necessary, however, to provide the comparison of the 2 control groups, as well, because major differences between the control groups will impact the interpretation of the patient versus control analyses. Direct comparison of the 2 control groups yielded, for the most part, very similar patterns of performance. The 2 groups did not differ in the accuracy of reading, in their ability to match morphed faces or in their matching faces across viewpoint.

The Alexia control group was slower than the Prosop control but only on a limited subset of the data (lexical decision, matching upright/inverted faces) and this may not be that surprising given the age differences between the 2 groups (Alexia control older than Prosop control). Some caution in interpretation may be warranted when the control groups differ. However, given the fact that the control groups are largely similar, and that there is no systematic difference between the groups when differences emerge (i.e., they do not differ across all face or across all word experiments), the comparisons between the patients and their matched controls are justified.

Taken together, there are 2 major novel findings of this study: both patient groups were impaired at both types of stimulus recognition, relative to their controls, but each was impaired to a greater extent in the stimulus class usually associated with their hemispheric side of lesion (Alexia more impaired at word reading than Prosop and Prosop more impaired at face processing than Alexia). In most instances, the pattern of impairment was qualitatively similar in the 2 groups. Thus, both groups were disproportionately slowed in word reading/lexical decision as a function of string length. That the Prosop patients showed this pattern after a right hemisphere lesion suggests that the letter-by-letter reading, typically ascribed to left VWFA lesions, applies to right hemisphere lesions too. This result implies that the right VWFA-equivalent might, under normal circumstances, contribute to the parallel letter processing thought to be a function of the left VWFA, and reflects the similarity in the mechanism supporting word recognition in both hemispheres, albeit with greater weight on the left side.

Closer scrutiny of the face recognition data also indicates qualitative similarity across the patient groups although not in all instances. Both patient groups were impaired at discriminating morphed faces although more markedly so in the Prosop than Alexia group. There was, however, a clear qualitative difference between the 2 groups in their response profile to matching upright versus inverted faces and this may be instructive. Whereas, consistent with many other reports (Farah et al. 1998), the Prosop patients performed relatively more accurately on inverted than upright faces, which contrasts with the normal pattern, this was not the case for the Alexia patients who showed an exaggerated form of the normal profile. One possible account of this difference between the patient groups may be that individual "parts" of visual words can map quasi-systematically to individual phonemes, so perhaps "holistic" visual processing is not as important for reading as for face recognition. Presumably local "parts" of faces are not that informative with respect to the identity of an individual person, with the result that mapping from a face percept to other information about the individual requires a more holistic kind of processing. Consistent with this, there is a longstanding proposal that the right hemisphere is more engaged in configural or holistic face processing whereas the left hemisphere is more engaged in featural or elemental processing (Hillger and Koenig 1991; Rossion et al. 2000). A lesion to the right hemisphere compromises the ability to represent faces configurally, with the result that primarily featural information is available, and this latter ability supports the processing of both upright and inverted faces (the advantage for inverted faces in prospopagnosia may reflect not just the diminishment of configural processing due to right hemisphere damage, but a noisy or corrupted contribution to task performance from this type of processing). The left hemisphere lesion in the Alexia group apparently does not impact configural processing but compromises part-based processing, thereby exaggerating the pattern of poorer performance with inverted faces (which require such processing). Finally, both groups were impaired at matching faces across changes in viewpoint, again to a greater degree for the Prosop patients than Alexia patients. Because error rate was relatively high in the Prosop group, drawing conclusions based on the RT data is not fully warranted.

As evident, both the Alexia and the Prosop groups are impaired relative to each other, depending on the domain, as well as relative to controls. It is the case, however, that almost every patient with brain damage is likely to be somewhat slower and perhaps less accurate on just about any task—and in particular, patients with visual problems are especially likely to be a bit slower and a bit less accurate on any challenging visual task. The question then arises as to whether the differences we observe here are simply a general result of the lesion or are specific to the types of processes that mediate face and/or word recognition. The challenge is then to find a domain in which we can establish normal performance for the patients. As laid out in the initial description of the patients, all 7 individuals perform within normal limits on finger-tapping speed (see Materials and Methods section) and, thus, they are not ubiquitously slowed in responding. The more telling issue, however, concerns their visual performance. All 7 patients perform within normal limits on the spatial tests of the VOSP. We also succeeded in testing 4 of the patients and a group of controls on a computerized line orientation judgment task and showed that the patients all fell within the normal distribution on this more exacting visual task. These findings attest to the fact that the patients' visual performance is not limited in an across-the-board or general fashion and, thus, the patterns of perturbation we observe are likely specific to the mechanisms under investigation, rather than a general consequence of brain damage or an impairment in elemental visual skills.

Taken together, these data suggest that even though both hemispheres contribute to face perception, they may do so differentially and a hemispheric division of labor is consistent with ongoing views about different computational roles played by each hemisphere. A review of the neuropsychological literature distinguishes between patients with right hemisphere lesions who show abnormalities in configural coding and those with left hemisphere lesions who are more compromised in the local analysis of the input (Gainotti and Marra 2011). This finding is also supported by a PET study demonstrating that the right fusiform gyrus was more activated when matching whole faces than face parts whereas this was reversed in the left homologous region (Rossion et al. 2000). Similarly, a recent fMRI study revealed that activation in the right fusiform gyrus correlated with categorical judgments (whether the image was of a face or not) whereas activation in the left hemisphere correlated with image-level face-semblance (Meng et al. 2012). As noted earlier, our claims of graded specialization of face and word processing within and between hemispheres is fully compatible with claims that, for both stimulus classes, each hemisphere makes somewhat different contributions to processing (although we would expect such hemispheric specializations also to differ in degree rather than kind).

Bilateral Processing of Words and Faces

The data presented here suggest that pure alexia and prosopagnosia may be homologs of each other, both arising from a lesion to a distributed system that underlies face recognition and word recognition. The emergence of face deficits after left hemisphere lesions and word deficits after right hemisphere lesions clearly indicate participation of both hemispheres in processing both stimulus classes albeit to varying degrees. There is, however, an alternative account that ought to be considered—that each class is represented solely in one hemisphere, with words on the left and faces on the right, and that a unilateral lesion suppresses the homologous region in the other hemisphere. Thus, for example, the word deficit in prosopagnosia might arise, not because orthography is represented in the right hemisphere, but because the right hemisphere focal lesion that gives rise to prosopagnosia inhibits the activation of the VWFA on the left (and the complement would be true for pure alexia). In fact, a recent imaging study of patient SM, one of the prosopagnosic subjects in the current study, reported that reduced fMRI activation and adaptation to object stimuli in tissue in and around his right hemisphere lesion were also observed in the homologous regions in his structurally intact left hemisphere (Konen et al. 2011).

Although we cannot definitively rule out this alternative interpretation, there are particular reasons why it seems implausible in this context. First, Konen et al. (2011) found normal activation in both hemispheres in SM when contrasting objects with fixation, indicating that the mere presence of a unilateral lesion does not suppress contralesional activation per se. Moreover, SM showed reduced neural responses (compared with controls) only for contrasts involving greater perceptual similarity (e.g., objects vs. scrambled objects), with the strongest effect coming from conditions requiring the most precise representational distinctions (e.g., repetition of the same vs. different object). Given the lack of perceptual similarity between faces and words, little if any contralesional suppression would be expected. Nevertheless, a definitive imaging study to examine the response of the intact hemisphere in the prosopagnosic and pure alexic individuals is warranted to definitively rule out this alternative. We already know from many imaging studies with normal individuals that there is bilateral activation for faces and for words in normal individuals (e.g., Hasson et al. 2002), compatible with the idea that both hemispheres are engaged in visual pattern recognition.

More generally, though, the Konen et al. (2011) pattern of results is more consistent with a cooperative rather than a competitive (or independent) relationship between homologous regions in the 2 hemispheres: in the intact brain, the regions interact and support each other in deriving a precise representation of a given stimulus, so that if one is lesioned, the normal support for the homologous region is reduced or eliminated [see (Farah and McClelland 1991), for a computational demonstration of this]. By contrast, on a view in which there are unilateral and independent face and word modules, as in a domain-specific account, there is no clear reason why lesioning one should have any effect on the other.

We (Plaut and Behrmann 2011) have recently articulated a theory, supported by a computational simulation, of how word and face processing become bilaterally but asymmetrically organized as a consequence of specific computational principles and constraints on neural learning (see Johnson 2011, for a similar, general perspective on cognitive and neural development, and Lambon Ralph et al. 2001; Plaut 2002, for related computational accounts of neuropsychological impairments in the domain of semantic memory). Both word and face recognition rely disproportionately on high-acuity visual information, and due to a topographic bias on learning (to minimize overall axon volume), their higher-level visual processes both become localized in the fusiform gyrus adjacent to retinotopic visual information from central vision (Levy et al. 2001; Hasson et al. 2002; Woodhead et al. 2011; Roberts et al. 2013). (In the model, fusiform cortex in each hemisphere corresponds to an internal layer of units adjacent to retinotopic visual input organized by retinal eccentricity, and learning within this layer is biased to favor connections from "nearby" input units.) Given that the 2 domains involve incompatible visual primitives, and that word representations need to interact with (typically) left-lateralized phonological and semantic information, competition between the 2 domains leads to graded hemispheric specialization, with words represented mostly on the left and faces mostly on the right. We demonstrated in our model that lesions of left-fusiform cortex adjacent to central visual information (analogous to the VWFA) produced a substantial impairment on word recognition but also a milder impairment on face recognition, whereas analogous lesions to right fusiform cortex (analogous to the FFA) produced the opposite pattern. These results are fully consistent with the findings of the current investigation.

A recent empirical study also provides support for this account (Dundas et al. 2012). This study examined the hemispheric superiority for faces and words in children (aged 7–9 years), young adolescents (aged 11–13 years), and adults in a half-field discrimination task. All groups showed a right visual field advantage for word discrimination, but only the adults showed a reliable left visual field advantage for face discrimination (even though the adolescents, as a group, were as accurate overall as the adults). Interestingly, the emergence of face lateralization in the younger groups was correlated with reading competence (even after regressing out age and overall face discrimination accuracy). The findings support the view that the hemispheric organization of face and word recognition do not develop independently, and that word lateralization, which emerges earlier, may drive later face lateralization.

Conclusion

Conventional wisdom holds that faces and words are independent domains of high-level vision subserved by independent neural mechanisms located in opposite hemispheres. On this view, lesions to the right hemisphere that impair face recognition (in prosopagnosia) should leave word recognition unaffected, and lesions to the left hemisphere that impair word recognition (in pure alexia) should leave face recognition unaffected. The current work shows that neither of these predictions is upheld. Instead, prosopagnosics have mild but reliable word recognition deficits, and pure alexics have mild but reliable face recognition deficits. The apparent co-mingling of face and word mechanisms is unexpected from a modular

perspective, but follows naturally as a consequence of an interactive, learning-based account in which neural processing for both faces and words are the result of an optimization procedure embodying specific computational principles and constraints.

Supplementary Material

Supplementary material can be found at: http://www.cercor.oxfordjournals.org/.

Funding

This work was supported by a grant from the National Science Foundation to MB and DP (BCS0923763), and by a grant from the Temporal Dynamics of Learning Center, SBE0542013 (G. Cottrell).

Notes

Some of the data were collected by Stephanie Manchin as part of her undergraduate thesis at Carnegie Mellon University. The authors also thank Lauren Lorenzi for help with data collection.

Some face stimuli were taken from the AR database (A. M. Martinez and R. Benavente, "The AR face database," CVC Tech. Report #24, 1998) and we thank the Computer Vision Laboratory, Faculty of Computer and Information Science, University of Ljubljana, Slovenia and the Secondary School Center, Velenje, Slovenia, for allowing us to use the CVL face Database (www.lrv.fri.uni-lj.sl/facedb.html). The morphed face images in this study were created from facial images provided by Sharon Gilaie-Dotan, and are fully described in the paper: Gilaie-Dotan S., Malach R. Sub-exemplar shape tuning in human face-related areas. Cereb. Cortex. 2007;17:325–338. We also thank Drs Troje and Bulthoff for the use of faces from the Max Planck database. *Conflict of Interest*: None declared.

References

Allison T, McCarthy G, Nobre AC, Puce A, Belger A. 1994. Human extrastriate visual cortex and the perception of faces, words, numbers and colors. Cereb Cortex. 5:544–554.

Anaki D, Kaufman Y, Freedman M, Moscovitch M. 2007. Associative (prosop)agnosia without (apparent) perceptual deficits: a case-study. Neuropsychologia. 45:1658–1671.

Atkinson AP, Adolphs R. 2011. The neuropsychology of face perception: beyond simple dissociations and functional selectivity. Philos Trans R Soc Lond B Biol Sci. 366:1726–1738.

Avidan G, Behrmann M. 2009. Functional MRI reveals compromised neural integrity of the face processing network in congenital prosopagnosia. Curr Biol. 19:1146–1150.

Avidan G, Tanzer M, Behrmann M. 2011. Impaired holistic processing in congenital prosopagnosia. Neuropsychologia. 49:2541–2552.

Barton JJS. 2011. Disorder of higher visual function. Curr Opin Neurol. 24:1–5.

Barton JJS. 2008. Structure and function in acquired prosopagnosia: lessons from a series of 10 patients with brain damage. J Neuropsychol. 2:197–225.

Barton JJS. 2009. What is meant by impaired configural processing in acquired prosopagnosia? Perception. 38:242–260.

Barton JJS, Press DZ, Keenan JP, O'Connor M. 2002. Lesions of the fusiform face area impair perception of facial configuration in prosopagnosia. Neurology. 58:71–78.

Behrmann M, Black SE, Bub D. 1990. The evolution of pure alexia: a longitudinal study of recovery. Brain Lang. 39:405–427.

Behrmann M, Kimchi R. 2003. What does visual agnosia tell us about perceptual organization and its relationship to object perception? J Exp Psychol: Hum Percept Perform. 29:19–42.

Behrmann M, Marotta J, Gauthier I, Tarr MJ, McKeeff TJ. 2005. Behavioral change and its neural correlates in visual agnosia after expertise training. J Cogn Neurosci. 17:554–568.

Behrmann M, McLeod J. 1995. Rehabilitation for pure alexia: efficacy of therapy and implications for models of normal word recognition. Neuropsychol Rehabil. 5:149–180.

Behrmann M, Nelson J, Sekuler E. 1998. Visual complexity in letter-by-letter reading: "pure" alexia is not so pure. Neuropsychologia. 36:1115–1132.

Behrmann M, Plaut DC, Nelson J. 1998. A literature review and new data supporting an interactive account of letter-by-letter reading. Cogn Neuropsychol. 15:7–51.

Behrmann M, Shallice T. 1995. Pure alexia: an orthographic not spatial disorder. Cogn Neuropsychol. 12:409–454.

Behrmann M, Williams P. 2007. Impairments in part-whole representations of objects in two cases of integrative visual agnosia. Cogn Neuropsychol. 24:701–730.

Benton AL, Sivan AB, Hamsher K, Varney NR, Spreen O. 1983. Contributions to neuropsychological assessment 2nd Ed., Oxford University Press, Inc.

Bodamer J. 1947. Die prosop-agnosie. Arch Psychiatr Nervkr. 179:6–53.

Bouvier SE, Engel SA. 2006. Behavioral deficits and cortical damage loci in cerebral achromatopsia. Cereb Cortex. 16:183–191.

Braet W, Wagemans J, Op de Beeck HP. 2012. The visual word form area is organized according to orthography. Neuroimage. 59:2751–2759.

Bruce V, Valentine T, Baddeley A. 1987. The basis of the 3/4 view advantage in face recognition. Appl Cogn Psychol. 1:109–120.

Bruce V, Young A. 1986. Understanding face recognition. Br J Psychol. 77:305–327.

Bukach CM, Bub DN, Gauthier I, Tarr MJ. 2006. Perceptual expertise effects are not all or none: spatially limited perceptual expertise for faces in a case of prosopagnosia. J Cogn Neurosci. 18:48–63.

Busigny T, Rossion B. 2010. Acquired prosopagnosia abolishes the face inversion effect. Cortex. 46:965–981.

Busigny T, Rossion B. 2011. Holistic processing impairment can be restricted to faces in acquired prosopagnosia: evidence from the global/local Navon effect. J Neuropsychol. 5:1–14.

Cohen L, Dehaene S. 2004. Specialization within the ventral stream: the case for the visual word form area. Neuroimage. 22:466–476.

Cohen L, Henry C, Dehaene S, Martinaud O, Lehericy S, Lemer C, Ferrieux S. 2004. The pathophysiology of letter-by-letter reading. Neuropsychologia. 42:1768–1780.

Cohen L, Martinaud O, Lemer C, Lehericy S, Samson Y, Obadia M, Dehaene S. 2003. Visual word recognition in the left and right hemispheres: anatomical and functional correlates of peripheral alexias. Cereb Cortex. 13:1313–1333.

Coslett HB, Monsul N. 1994. Reading with the right hemisphere: evidence from transcranial magnetic stimulation. Brain and Language. 46:198–211.

Crawford JR, Garthwaite PH. 2004. Statistical methods for single-case studies in neuropsychology: comparing the slope of a patient's regression line with those of a control sample. Cortex. 40:533–548.

Damasio AR, Damasio H, Hoesen GWV. 1982. Prosopagnosia: anatomic basis and behavioral mechanisms. Neurology. 32:331–341.

Davous P, Boller F. 1994. Transcortical alexia with agraphia following a right temporo-occipital hematoma in a right-handed patient. Neuropsychologia. 32:1263–1272.

Dehaene S, Cohen L. 2007. Cultural recycling of cortical maps. Neuron. 56:384–398.

Dehaene S, Cohen L. 2011. The unique role of the visual word form area in reading. Trends Cogn Sci. 15:254–262.

Dehaene S, Cohen L, Sigman M, Vinckier F. 2005. The neural code for written words: a proposal. Trends Cogn Sci. 9:335–341.

Dundas E, Plaut DC, Behrmann M. 2012. The joint development of hemispheric lateralization for words and faces. J Exp Psychol Gen (in press).

Epstein RA. 2011. Cognitive neuroscience: scene layout from vision and touch. Curr Biol. 21:R437–R438.

Epstein RA, Harris A, Stanley D, Kanwisher N. 1999. The parahippocampal place area: recognition, navigation, or encoding? Neuron. 23:115–125.

Farah MJ, Levinson KL, Klein KL. 1995. Face perception and within-category discrimination in prosopagnosia. Neuropsychologia. 33:661–674.
Farah MJ, McClelland JL. 1991. A computational model of semantic memory impairment: modality-specificity and emergent category-specificity. J Exp Psychol Gen. 120:339–357.
Farah MJ, Wilson KD, Drain M, Tanaka JN. 1998. What is "special" about face perception? Psychol Rev. 105:482–498.
Feinberg TE, Schindler RJ, Ochoa E, Kwan PC, Farah MJ. 1994. Associative visual agnosia and alexia without prosopagnosia. Cortex. 30:395–412.
Gainotti G, Marra C. 2011. Differential contribution of right and left temporo-occipital and anterior temporal lesions to face recognition disorders. Front Hum Neurosci. 5:55.
Gauthier I, Behrmann M, Tarr MJ. 1999. Can face recognition really be dissociated from object recognition? J Cogn Neurosci. 11:349–370.
Gauthier I, Tarr MJ, Anderson AW, Skudlarski P, Gore JC. 1999. Activation of the middle fusiform "face area" increases with expertise in recognizing novel objects. Nat Neusci. 2:568–573.
Gauthier I, Tarr MJ, Moylan J, Anderson AW, Skudlarski P, Gore JC. 2000. Does visual subordinate-level categorisation engage the functionally defined fusiform face area? Cogn Neuropsychol. 17:143–164.
Gobbini MI, Haxby JV. 2007. Neural systems for recognition of familiar faces. Neuropsychologia. 7:32–41.
Grill-Spector K, Sayres R, Ress D. 2006. High-resolution imaging reveals highly selective nonface clusters in the fusiform face area. Nat Neurosci. 9:1177–1185.
Hanson SJ, Schmidt A. 2011. High-resolution imaging of the fusiform face area (FFA) using multivariate non-linear classifiers shows diagnosticity for non-face categories. Neuroimage. 54: 1715–1734.
Hasson U, Levy I, Behrmann M, Hendler T, Malach R. 2002. Center-biased representation for characters in the human ventral visual stream. Neuron. 34:479–490.
Haxby JV, Grady CL, Ungerleider LG, Horwitz B. 1991. Mapping the functional neuroanatomy of the intact human brain with brain work imaging. Neuropsychologia. 29:539–555.
Haxby JV, Guntupalli JS, Connolly AC, Halchenko YO, Conroy BR, Gobbini MI, Ramadge PJ. 2011. A common, high-dimensional model of the representational space in human ventral temporal cortex. Neuron. 72:404–416.
Haxby JV, Hoffman EA, Gobbini MI. 2000. The distributed human neural system for face perception. Trends Cogn Sci. 4:223–233.
Hillger LA, Koenig O. 1991. Separable mechanisms in face processing: evidence from hemispheric specialization. J Cogn Neurosci. 3:42–58.
Humphreys K, Avidan G, Behrmann M. 2007. A detailed investigation of facial expression processing in congenital prosopagnosia as compared to acquired prosopagnosia. Exp Brain Res. 176:356–373.
Ishai A, Ungerleider LG, Haxby JV. 2000. Distributed neural systems for the generation of visual images. Neuron. 28:979–990.
Ishai A, Ungerleider LG, Martin A, Haxby JV. 2000. The representation of objects in the human occipital and temporal cortex. J Cogn Neurosci. 12:35–51.
Johnson MH. 2011. Interactive specialization: a domain-general framework for human functional brain development? Dev Cogn Neurosci. 1:7–21.
Kanwisher N. 2010. Functional specificity in the human brain: a window into the functional architecture of the mind. Proc Natl Acad Sci USA. 107:11163–11170.
Kanwisher N, McDermott J, Chun MM. 1997. The fusiform face area: a module in human extrastriate cortex specialized for face perception. J Neurosci. 17:4302–4311.
Kanwisher N, Stanley D, Harris A. 1999. The fusiform face area is selective for faces not animals. Neuroreport. 10:183–187.
Kherif F, Josse G, Price CJ. 2011. Automatic top-down processing explains common left occipito-temporal responses to visual words and objects. Cereb Cortex. 21:103–114.
Kleinschmidt A, Cohen L. 2006. The neural bases of prosopagnosia and pure alexia: recent insights from functional neuroimaging. Curr Opin Neurol. 19:386–391.
Konen CS, Behrmann M, Nishimura M, Kastner S. 2011. The functional neuroanatomy of object agnosia: a case study. Neuron. 71:49–60.
Kriegeskorte N, Formisano E, Sorger B, Goebel R. 2007. Individual faces elicit distinct response patterns in human anterior temporal cortex. Proc Natl Acad Sci USA. 104:20600–20605.
Kronbichler M, Hutzler F, Wimmer H, Mair A, Staffen W, Ladurner G. 2004. The visual word form area and the frequency with which words are encountered: evidence from a parametric fMRI study. Neuroimage. 21:946–953.
Kucera F, Francis WN. 1967. Computational analysis of present-day American English. Providence (RI): Brown University Press.
Lambon Ralph MA, McClelland JL, Patterson K, Galton CJ, Hodges JR. 2001. No right to speak? The relationship between object naming and semantic impairment: neuropsychological evidence and a computational model. J Cogn Neurosci. 13:341–356.
Levine D, Calvanio R. 1989. "Prosopagnosia: a defect in visual configural processing." Brain Cogn. 10:149–170.
Levy I, Hasson U, Hendler T, Malach R. 2001. Center-periphery organization of human object areas. Nat Neurosci. 4:533–539.
Marinkovic K, Dhond RP, Dale AM, Glessner M, Carr V, Halgren E. 2003. Spatiotemporal dynamics of modality-specific and supramodal word processing. Neuron. 38:487–497.
Marotta JJ, Behrmann M, Genovese C. 2001. A functional MRI study of face recognition in patients with prosopagnosia. Neuroreport. 12:959–965.
Marotta JJ, Genovese CR, Behrmann M. 2001. A functional MRI study of face recognition in patients with prosopagnosia. Neuroreport. 12:1581–1587.
Marotta JJ, McKeeff TJ, Behrmann M. 2002. The effects of inversion and rotation on face processing in prosopagnosia. Cogn Neuropsychol. 19:31–47.
Mattson AJ, Levin HS, Grafman J. 2000. A case of prosopagnosia following moderate closed head injury with left hemisphere focal lesion. Cortex. 36:125–137.
McCandliss BD, Cohen L, Dehaene S. 2003. The visual word form area: expertise for reading in the fusiform gyrus. Trends Cogn Sci. 7:293–299.
McKeeff TJ, Behrmann M. 2004. Relating naming latency and covert processing in pure alexia. Cogn Neuropsychol. 21:443–458.
McKone E, Crookes K, Jeffery L, Dilks DD. 2012. A critical review of the development of face recognition: Experience is less important than previously believed. Cogn Neuropsychol. doi:10.1080/02643294.2012.660138.
McKone E, Robbins R. 2011. Are faces special? In: Calder AJ, Rhodes G, Johnson MJ, Haxby JV, editors. The Oxford handbook of face perception. Oxford (UK): Oxford University Press. p. 147–176.
Meadows JC. 1974. The anatomical basis of prosopagnosia. J Neurol Neurosurg Psychiatry. 37:489–501.
Meng M, Cherian T, Singal G, Sinha P. 2012. Lateralization of face processing in the human brain. Proc Biol Sci. 22:2052–2061.
Montant M, Behrmann M. 2001. Phonological activation in pure alexia. Cogn Neuropsychol. 18:697–727.
Morton J, Patterson K. 1980. A new attempt at an interpretation, or, and attempt at a new interpretation. In: Coltheart M, Marshall J, Patterson KP, editors. Deep dyslexia. London (UK): Routledge. pp. 99–118.
Nazir TA, Ben-Boutayab N, Decoppet N, Deutsch A, Frost R. 2004. Reading habits, perceptual learning, and recognition of printed words. Brain Lang. 88:294–311.
Nestor A, Behrmann M, Plaut DC. 2013. The neural basis of visual word form processing—a multivariate investigation. Cereb Cortex. 23:1673–1684.
Nestor A, Plaut DC, Behrmann M. 2011. Unraveling the distributed neural code of facial identity through spatiotemporal pattern analysis. Proc Natl Acad Sci USA. 108:9998–10003.
Nishimura M, Doyle J, Humphreys K, Behrmann M. 2010. Probing the face-space of individuals with prosopagnosia. Neuropsychologia. 48:1828–1841.

Ogden JA. 1984. Dyslexia in a right-handed patient with a posterior lesion of the right cerebral hemisphere. Neuropsychologia. 22:265–280.
O'Toole AJ, Edelman S, Bulthoff HH. 1998. Stimulus-specific effects in face recognition over changes in viewpoint. Vision Res. 38:2351–2363.
Peelen MV, Downing PE. 2005. Selectivity for the human body in the fusiform gyrus. J Neurophysiol. 93:603–608.
Plaut DC. 2002. Graded modality-specific specialization in semantics: a computational account of optic aphasia. Cogn Neuropsychol. 19:603–639.
Plaut D, Behrmann M. 2011. Complementary neural representations for faces and words: a computational exploration. Cogn Neuropsychol. 28:251–275.
Polk TA, Farah MJ. 2002. Functional MRI evidence for an abstract, not perceptual, word-form area. J Exp Psychol. 131:65–72.
Polk TA, Stallcup M, Aguirre GK, Alsop DC, D'Esposito M, Detre JA, Farah MJ. 2002. Neural specialization for letter recognition. J Cogn Neurosci. 14:145–159.
Price CJ, Devlin JT. 2011. The interactive account of ventral occipitotemporal contributions to reading. Trends Cogn Sci. 15: 246–253.
Price CJ, Devlin JT. 2003. The myth of the visual word form area. Neuroimage. 19:473–481.
Price CJ, Mechelli A. 2005. Reading and reading disturbance. Curr Opin Neurobiol. 15:231–238.
Puce A, Allison T, Asgari M, Gore JC, McCarthy G. 1996. Differential sensitivity of human visual cortex to faces, letterstrings, and textures: a functional magnetic resonance imaging study. J Neurosci. 16:5205–5215.
Puce A, Allison T, Gore JC, McCarthy G. 1995. Face-sensitive regions in human extrastriate cortex studied by functional MRI. Journal of Neurophysiology. 74:1192–1199.
Rajimehr R, Young JC, Tootell RB. 2009. An anterior temporal face patch in human cortex, predicted by macaque maps. Proc Natl Acad Sci USA. 106:1995–2000.
Roberts DJ, Woollams AM, Kim E, Beeson PM, Rapscak SZ, Lambon Ralph MA. 2013. Efficient visual object and word recognition relies on high spatial frequency coding in the left posterior fusiform gyrus: evidence from a case-series of patients with ventral occipitotemporal cortex damage. Cereb Cortex. 23:2568–2580.
Rossion B, Dricot L, Devolder A, Bodart JM, Crommelinck M, De Gelder B, Zoontjes R. 2000. Hemispheric asymmetries for whole-based and part-based face processing in the human fusiform gyrus. J Cogn Neurosci. 12:793–802.
Salvan CV, Ulmer JL, DeYoe EA, Wascher T, Mathews VP, Lewis JW, Prost RW. 2004. Visual object agnosia and pure word alexia: correlation of functional magnetic resonance imaging and lesion localization. J Comput Assist Tomogr. 28(1):63–67.
Schwarzlose RF, Baker CI, Kanwisher N. 2005. Separate face and body selectivity on the fusiform gyrus. J Neurosci. 25(47):11055–11059.
Sergent J, Ohta S, MacDonald B. 1992. Fuctional neuroanatomy of face and object processing. Brain. 115:15–36.
Sergent J, Signoret JL. 1992. Functional and anatomical decomposition of face processing; Evidence from prosopagnosia and PET study of normal subjects. Phil Trans R Soc Lond B. 335:55–62.
Sewards TV. 2011. Neural structures and mechanisms involved in scene recognition: a review and interpretation. Neuropsychologia. 49(3):277–298.
Sigman M, Pan H, Yang Y, Stern E, Silbersweig D, Gilbert CD. 2005. Top-down reorganization of activity in the visual pathway after learning a shape identification task. Neuron. 46(5):823–835.
Starrfelt R, Behrmann M. 2011. Number reading in pure alexia–a review. Neuropsychologia. 49(9):2283–2298.
Starrfelt R, Gerlach C. 2007. The visual what for area: words and pictures in the left fusiform gyrus. Neuroimage. 35(1):334–342.
Starrfelt R, Habekost T, Leff AP. 2009. Too little, too late: reduced visual span and speed characterize pure alexia. Cereb Cortex. 19 (12):2880–2890.
Strauss E, Sherman EMS, Spreen O. 2006. A compendium of neuropsychological tests: administration, norms and commentary. Oxford University Press.
Tagamets MA, Novick JM, Chalmers ML, Friedman RB. 2000. A parametric approach to orthographic processing in the brain: an fMRI study. J Cogn Neurosci. 12:281–297.
Thomas C, Avidan G, Humphreys K, Jung KJ, Gao F, Behrmann M. 2009. Reduced structural connectivity in ventral visual cortex in congenital prosopagnosia. Nat Neurosci. 12:29–31.
Thomas C, Moya L, Avidan G, Humphreys K, Jung KJ, Peterson MA, Behrmann M. 2008. Reduction in white matter connectivity, revealed by diffusion tensor imaging, may account for age-related changes in face perception. J Cogn Neurosci. 20:268–284.
Vinckier F, Dehaene S, Jobert A, Dubus JP, Sigman M, Cohen L. 2007. Hierarchical coding of letter strings in the ventral stream: dissecting the inner organization of the visual word-form system. Neuron. 55:143–156.
Warrington EK, James M. 1991. Visual object and space perception battery. Oxford, UK: Psychorp, Pearson.
Willems RM, Peelen MV, Hagoort P. 2010. Cerebral lateralization of face-selective and body-selective visual areas depends on handedness. Cereb Cortex. 20:1719–1725.
Williams MA, Savage G, Halmagyi M. 2006. Abnormal configural face perception in a patient with right anterior temporal lobe atrophy. NeuroCase. 12:286–291.
Woodhead ZVJ, Wise RJS, Sereno M, Leech R. 2011. Dissociation of sensitivity to spatial frequency in word and face preferential areas of the fusiform gyrus. Cereb Cortex. 21:2307–2312.
Wright ND, Mechelli A, Noppeney U, Veltman DJ, Rombouts SA, Glensman J, Price CJ. 2008. Selective activation around the left occipito-temporal sulcus for words relative to pictures: individual variability or false positives? Hum Brain Mapp. 29:986–1000.
Yovel G, Tambini A, Brandman T. 2008. The asymmetry of the fusiform face area is a stable individual characteristic that underlies the left-visual-field superiority for faces. Neuropsychologia. 46:3061–3068.

Behrmann and Plaut
Supplementary material: Bilateral hemispheric processing of words and faces: Evidence from word impairments in prosopagnosia and face impairments in pure alexia

Supplementary experiment:

Introduction:

The key experimental findings indicate that there are impairments in both face and word processing in individuals with prosopagnosia and with pure alexia, relative to control participants. We have suggested that these impairments derive from the failure to engage in fine-grained pattern recognition. We have also proposed that the asymmetry (prosopagnosics poorer on faces than words and pure alexics poorer on words than faces) results from the optimization of word processing in the left hemisphere (to keep connection length to language areas short) and that the optimization of face processing in the right hemisphere may be the result of the competition for representation between faces and words which are geometrically so different and therefore unable to be equivalently represented by the same underlying mechanisms. There is, however, an alternative possible explanation and that is that both patient groups are impaired at all types of visual processing (although this explanation would still have to concede that the impairment was somewhat specific to the side of the lesion given the asymmetric manifestation of the face/word deficit in the two patient groups). Nevertheless, we conducted a further experiment to determine the specificity of the visual deficit in the patients. The prediction based on the account we have explicated is that the patients should evince normal visual function in tasks that do not require fine-grained pattern recognition. To this end, we tested those patients whom we were still able to contact and matched controls on their ability to perform line orientation judgments. This task is considered challenging for patients with apperceptive-type agnosias but should be performed normally by patients with lesions such as those included in this study.

Participants

Two prosopagnosic (SM, CR) and two alexic (EL, SH) were available for further testing, along with a group of 11 control participants. Contained in the group of controls were matched controls for the patients but because these experiments have not been independently validated, we also obtained control data from additional participants so as to have a more representative sample of normal performance.

Experiment 1:

Materials and Procedure

This experiment is a somewhat modified, computer-implemented version of the well known Benton Judgment of Line Orientation Test (Benton et al., 1983). We elected to use this experiment because of its sensitivity to perceptual deficits and its robustness over a relatively small number of trials (Qualls et al., 2000). We chose to implement a computerized version so that we might measure RT as well as accuracy lest the patients be trading speed for accuracy in their responses.

On a single trial, two line segments, randomly selected from 11 lines oriented at 15 degrees and ranging from 0-180 degrees, appeared at the top of the computer screen (see Supplementary Figure 1). At the bottom of the screen, all 11

lines are shown, along with a number to identify each line. A black bar separates the samples from the response lines. The display remains on the screen for unlimited duration and participants press a button (buttons on keyboard 1-9, with 2 additional buttons labeled for 10 and 11) to indicate the numbers of the two lines that appear at the top of the screen. Both accuracy and RT were recorded for responses to each of the two lines. Five practice trials were provided and then a total of 180 trials were completed by each participant.

Results

An ANOVA with the 4 patients and 11 controls, conducted on the accuracy and RT of the responses to each of the two lines, revealed no difference between the patients and controls on either dependent measure (accuracy: p=.87; RT: p=.581). Both accuracy and RT was better overall for the first than the second line [(accuracy: (F(1,13)=9.86, p=.008); RT (F(1,13)=20.2, p<.001)] but this held equally across the two groups [(no line x group interaction; accuracy: (F(1,13)=.025, p=.87); RT: (F(1,13=-.084, p=.777)].

In addition to the group measurements reported above, we also determined whether any individual patient fell outside the performance of the control group. Using the Crawford modified t-test procedure (Crawford and Garthwaite, 2002, Crawford and Garthwaite, 2004), we examined each patient's accuracy and RT for each of the two lines against the control group. No patient showed statistically different performance from the control group on any of the measures, consistent with the absence of a group difference.

Discussion

The assessment of the line orientation performance of four of the patients reveals normal performance, as assessed by comparing the group means and by examining the performance of each individual patient. We also note that these four patients are not milder than the other patients (see individual data in Table 2) and so, although we did not evaluate each patient, that we see normal visual skills in the line orientation (and in the VOSP, see under patient description in main paper) suggests that a difference in visual ability across the board is unlikely to account for the impairment in face and word recognition (and their asymmetry), that we observe in the key experiments.

References:

BENTON, A. L., SIVAN, A. B., HAMSHER, K., VARNEY, N. R. & SPREEN, O. 1983. *Contributions to neuropsychological assessment 2nd Ed.,* Oxford, UK, Oxford University Press, Inc.

CRAWFORD, J. R. & GARTHWAITE, P. H. 2002. Investigation of the single test score in neuropsychology: confidence limits on the abnormality of test scores and test score differences. *Neuropsychologia,* 40**,** 1196-1208.

CRAWFORD, J. R. & GARTHWAITE, P. H. 2004. Statistical methods for single-case studies in neuropsychology: comparing the slope of a patient's regression line with those of a control sample. *Cortex,* 40**,** 533-548.

QUALLS, C. E., BLIWISE, N. G. & STRINGER, A. Y. 2000. Short forms of the Benton Judgment of Line Orientation Test: development and psychometric

properties. *Archives of clinical neuropsychology : the official journal of the National Academy of Neuropsychologists,* 15**,** 159-63.

Figure S1: Example of display used to assess line orientation judgements in the patients and controls.