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Acquired prosopagnosia without word recognition deficits

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It has long been suggested that face recognition relies on specialized mechanisms that are not involved in visual recognition of other object categories, including those that require expert, fine-grained discrimination at the exemplar level such as written words. But according to the recently proposed many-to-many theory of object recognition (MTMT), visual recognition of faces and words are carried out by common mechanisms [Behrmann, M., & Plaut, D. C. (2013). Distributed circuits, not circumscribed centers, mediate visual recognition. *Trends in Cognitive Sciences, 17,* 210–219]. MTMT acknowledges that face and word recognition are lateralized, but posits that the mechanisms that predominantly carry out face recognition still contribute to word recognition and vice versa. MTMT makes a key prediction, namely that acquired prosopagnosics should exhibit some measure of word recognition deficits. We tested this prediction by assessing written word recognition in five acquired prosopagnosic patients. Four patients had lesions limited to the right hemisphere while one had bilateral lesions with more pronounced lesions in the right hemisphere. The patients completed a total of seven word recognition tasks: two lexical decision tasks and five reading aloud tasks totalling more than 1200 trials. The performances of the four older patients (3 female, age range 50–64 years) were compared to those of 12 older controls (8 female, age range 56–66 years), while the performances of the younger prosopagnosic (male, 31 years) were compared to those of 14 younger controls (9 female, age range 20–33 years). We analysed all results at the single-patient level using Crawford's *t*-test. Across seven tasks, four prosopagnosics performed as quickly and accurately as controls. Our results demonstrate that acquired prosopagnosia can exist without word recognition deficits. These findings are inconsistent with a key prediction of MTMT. They instead support the hypothesis that face recognition is carried out by specialized mechanisms that do not contribute to recognition of written words.

Keywords: prosopagnosia; face; word; recognition; dissociation

1. Introduction

Nearly all adults in the modern world are expert at recognizing faces and words. Face recognition is critical to effective social interactions, while reading ability is central to many professions and cultural domains. Face and word recognition pose similar computational demands in that both require within-class discrimination of subtly differing

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exemplars. Faces and words also preferentially activate category-selective regions in the ventral visual pathway. These considerations raise a fundamental question: Do face and word recognition depend on the same high-level mechanisms, or do they rely on independent mechanisms?

According to the many-to-many theory (MTMT) of visual object recognition (Behrmann & Plaut, 2013, 2014), object recognition is carried out by distributed networks of cortical areas that are each involved in recognizing many types of objects. As a primary evidence, MTMT asserts that face and word recognition rely on common processes rather than on independent mechanisms. These common mechanisms are said to result from the manner in which the visual system responds to the similar computational demands of face and word recognition. MTMT, however, acknowledges the hemispheric asymmetry of face and word processing. According to MTMT, while face recognition is predominantly carried out in the right hemisphere, the left hemisphere also contributes to it, and while word recognition is primarily dependent on the left hemisphere, it also relies on right-hemisphere processes. Thus although face and word recognition are lateralized, there are no mechanisms that are dedicated to face or word recognition alone.

MTMT makes a key prediction: Face and word recognition deficits in brain-damaged patients should co-occur. The prediction has two parts. First, face recognition deficits in acquired prosopagnosia should be accompanied by some degree of word recognition deficits. Second, word recognition deficits in pure alexia (i.e., alexia without agraphia) should be accompanied by some degree of face recognition deficits. These predictions are stated clearly by Behrmann and Plaut (2014, p. 1104):

> 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."

At first sight, these predictions seem to have been falsified by a long list of dissociations between prosopagnosia and pure alexia (Susilo & Duchaine, 2013). A comprehensive review by Farah (1991) tallied 58 reports in which impairment with one category (e.g., faces) was not accompanied by deficit with the other category (e.g., words). Indeed, the double dissociation between prosopagnosia and pure alexia was central to Farah's two-system theory of visual recognition, which posits two systems to carry out object recognition: one that represents objects in a holistic manner and another that uses part-based representations (Farah, 1991). This theory suggests that face recognition is especially reliant on holistic representations, word recognition is especially reliant on part-based representations, and recognition of other objects depends on some combinations of both types of representations.

However, a closer inspection of the reports suggests that the ostensibly nonimpaired category was rigorously tested only in very few cases (Plaut & Behrmann, 2013). In most cases the nonimpaired category was examined only with one or two tests, which means subtle deficits might have gone unnoticed. A notable exception is patient C. K. (Behrmann, Winocur, & Moscovitch, 1992), a pure alexic who performed virtually at chance when tested with multiple word recognition tasks (Behrmann, Moscovitch, & Winocur, 1994). Despite his pure alexia, C.K. showed completely normal recognition of upright faces as examined in 21 experiments (Moscovitch & Moscovitch, 2000; Moscovitch, Winocur, & Behrmann, 1997). C.K.'s results suggest that face recognition is carried out by mechanisms independent from those used for word recognition, although some authors argue that it is difficult to generalize the case of C.K. because his brain profile was atypical: C.K. had bilateral posterior occipital thinning without noticeable lesion (Plaut & Behrmann, 2013).

Behrmann and Plaut (2014) tested the predictions of MTMT in three prosopagnosic patients with right-hemisphere lesions and in four alexia patients with left-hemisphere lesions. Consistent with the predictions, they observed some word recognition deficits in the prosopagnosic group and some face recognition deficits in the alexic group. The conclusion of this study, though, is complicated by two issues. First, evidence of association tends to be theoretically weaker than evidence of dissociation (Coltheart, 2002; Shallice, 1988). An association between face and word recognition deficits in the same patient may be caused either by a single impairment to common mechanisms or by separate impairments to independent mechanisms. Second, the three prosopagnosics in Behrmann and Plaut (2014)—namely, S.M., C.R., and R.N.—had problems recognizing objects even at the basic level (Gauthier, Behrmann, & Tarr, 1999; Marotta, McKeeff, & Behrmann, 2002). In addition, S.M. showed functional abnormalities in the left hemisphere despite its intact structure, suggesting that her lesion might not be strictly unilateral (Konen, Behrmann, Nishimura, & Kastner, 2011). All this suggests that the prosopagnosics' deficits with faces and words might stem from broader visual problems rather than from face and word recognition mechanisms per se.

Another recent study tested the prediction of MTMT by assessing word recognition and text style recognition (computer fonts and handwriting style) in acquired prosopagnosia (Hills, Pancaroglu, Duchaine, & Barton, 2015). This study found intact processing of words in six prosopagnosics with right-hemisphere damage, but slightly elevated word-length effects in five prosopagnosics with bilateral lesions. Interestingly, nearly all prosopagnosics had some difficulties recognizing fonts and handwriting, as assessed in a card-sorting format in which participants had to group words based on fonts or handwriting regardless of content. Overall, this study shows that acquired prosopagnosia can exist without problems recognizing words. However, this study's conclusions about word recognition in prosopagnosia is limited in that it tested reading aloud with only one task and did not assess lexical decision making. This leaves open the possibility that the prosopagnosics had mild word recognition deficits.

Because MTMT suggests that word processing deficits in prosopagnosia may be subtle and therefore challenging to detect, here we thoroughly assessed word recognition using a variety of tasks. We tested five prosopagnosic patients. Two features of our study are worth noting. First, our study is methodologically powerful because we used a total of seven word recognition tasks: two lexical decision tasks and five reading aloud tasks involving more than 1200 trials. As a comparison, Behrmann and Plaut (2014) used only one lexical task and one reading task totalling 180 trials, whereas Hills et al. (2015) used one reading task with 140 trials. Second, in performing statistical comparisons for individual patients, we chose not to correct for multiple comparisons, thus increasing the likelihood of detecting subtle deficits. If MTMT is correct, all prosopagnosics should exhibit some measure of word recognition deficits. But if face and word recognition are carried out by independent mechanisms, the prosopagnosics whose impairment is restricted to face processing should demonstrate normal word recognition ability.

2. Method

2.1. *Acquired prosopagnosic patients*

The five acquired prosopagnosic patients came to our attention after each registered at *faceblind.org*. All of them complained of severe face recognition problems in daily life following episodes of brain injury. None reported premorbid cognitive deficits or developmental abnormalities. As shown in Table 1, their prosopagnosia was confirmed using three tests of face recognition: (a) Cambridge Face Memory Test (CFMT, Duchaine & Nakayama, 2006), (b) Famous Face Test (FFT, Duchaine & Nakayama, 2005), and (c) Old–New Face Recognition Test (Duchaine, Yovel, Butterworth, & Nakayama, 2006). Table 1 also shows

Table 1. Scores of the prosopagnosic patients on tests of face recognition, object recognition, and general visual abilities.

Test	Herschel	Galen	Faith	Lily	Kili	Control *M*	Control *SD*	Max score
Face recognition								
Cambridge Face Memory Test	31[a]	29[a]	26[a]	34[a]	36[a]	59.6	7.6	72
Famous Face Test	3[a]	30[a]	20[a]	37[a]	23[a]	52	5.18	60
Old–new test for faces	0.85[a]	0.66[a]	0.6[a]	n/a	0.64[a]	0.96	0.02	1
Object recognition								
Cambridge Car Memory Test	54	65	45	37[b]	n/a	57.43/ 50.44[c]	8.31/7.15[c]	72
Cambridge Body Memory Test	n/a	46	41	45	n/a	49.68	7.1	72
Cambridge Hair Memory Test	44	43	45	n/a	n/a	50.85	6.05	72
Abstract Art Memory Test	n/a	31	28	n/a	30	31.96	6.67	50
Verbal Paired Memory Test	n/a	17	13	n/a	5[a]	15.25	4.75	25
Old–new test for houses	0.96	n/a	n/a	n/a	0.86[a]	0.96	0.03	1
Old–new test for cars	0.95	n/a	n/a	n/a	0.64[a]	0.94	0.04	1
Old–new test for horses	0.86[b]	n/a	n/a	n/a	0.7[a]	0.94	0.03	1
General visual abilities								
BORB length	28	n/a	n/a	27	23[a]	26.9	1.6	30
BORB size	28	n/a	n/a	29	25	27.3	2.4	30
BORB orientation	27	n/a	n/a	25	23	24.8	2.6	30
BORB position of gap	37	n/a	n/a	39	36	35.1	4	40
Circle size	n/a	0.96	0.88	n/a	n/a	0.79	0.11	1
Oval shape	n/a	0.54	0.38	n/a	n/a	0.61	0.13	1
Line length	n/a	0.71	0.71	n/a	n/a	0.7	0.13	1
Line angle	n/a	0.92	0.58	n/a	n/a	0.66	0.14	1
Dots distance	n/a	0.63	0.63	n/a	n/a	0.61	0.1	1
Spatial frequency	n/a	0.67	0.46	n/a	n/a	0.67	0.17	1

Note: BORB = Birmingham Object Recognition Battery.
[a]Impaired score.
[b]Borderline score.
[c]Control data are provided separately for males (left) and females (right) due to a significant sex difference on the Cambridge Car Memory Test (Dennett et al., 2012).

the patients' scores on various tests of object recognition and general visual abilities. Figure 1 presents their structural scans, while Table 2 summarizes the status of their face-selective regions. The profile of each prosopagnosic patient is described below.

Herschel

Herschel is a right-handed male born in 1956. He was first reported in Rezlescu, Pitcher, and Duchaine (2012). He has an astronomy degree and works in science and technology. In February

Table 2. Status of bilateral face-selective regions (FFA, OFA, pSTS) in the prosopagnosic patients.

Patient	lFFA	lOFA	lpSTS	rFFA	rOFA	rpSTS
Herschel	+	–	+	+	+	+
Galen	+	+	+	–	–	+
Faith	+	+	+	–	–	–
Lily	+	+	+	+	+	+
Kili	+	+	+	+	+	+

Notes: Face-selective regions: FFA = fusiform face area; OFA = occipital face area; pSTS = posterior superior temporal sulcus. l = left; r = right. Missing regions are indicated (–). The functional localizer protocol for Herschel was described in Pitcher, Dilks, Saxe, Triantafyllou, and Kanwisher (2011); for the other patients it was described in Fox, Iaria, and Barton (2011).

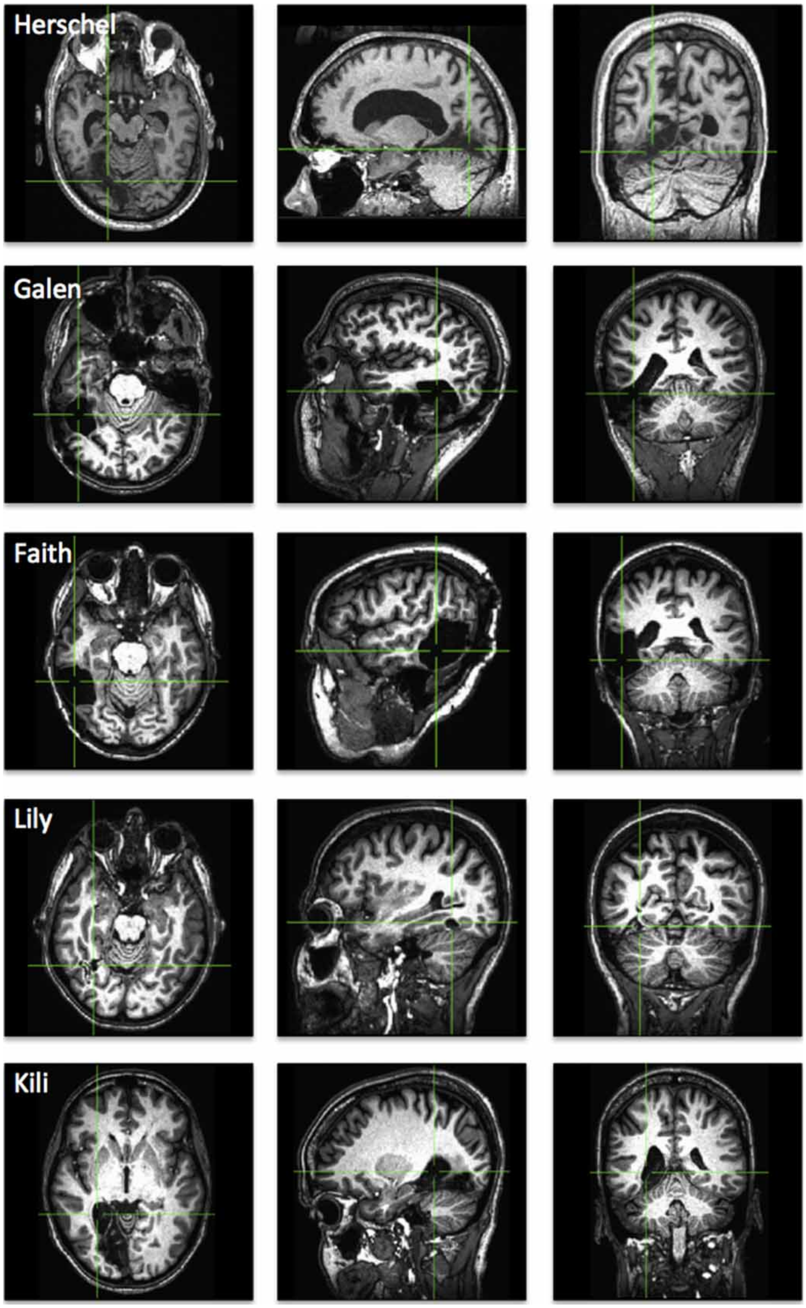


Figure 1. Structural scans of the prosopagnosic patients. Top to bottom: Herschel, Galen, Faith, Lily, Kili. Left to right: axial, coronal, sagittal views. Images are mirror-reversed following radiological convention.

2008 Herschel suffered a stroke that was followed by prosopagnosia and other visual problems including navigation and an upper left quandrantanopia. Four months later he had a second stroke that resulted in temporary colour distortions and an upper right quandrantanopia. Two months after that, he suffered two transient ischaemic attacks causing temporary loss of control of the left leg and temporary speech problems. A magnetic resonance imaging (MRI) examination showed bilateral occipitotemporal lesions that are more pronounced on the right hemisphere. Currently Herschel reports only prosopagnosia and an almost complete upper visual field loss except one third of upper right. Herschel's general visual ability was in the normal range, as assessed using subsets of the Birmingham Object Recognition Battery (BORB, Riddoch & Humphreys, 1993). Herschel also showed normal performance when discriminating exemplars of a wide range of object categories including scenes, houses, tools, cars, guns, sunglasses (Rezlescu et al., 2012), and greebles (Rezlescu, Pitcher, Barton, & Duchaine, 2014), though he exhibited deficits when recognizing exemplars of horses (Rezlescu et al., 2012).

Galen

Galen is a right-handed male born in 1982. He was first reported in Susilo, Yovel, Barton, and Duchaine (2013) and subsequently in Susilo, Yang, Potter, Robbins, and Duchaine (2015) and Yang, Susilo, and Duchaine (2014). Galen works as a physician in a Veterans Administration hospital. In 2004 Galen had a craniotomy for an arteriovenous malformation in the right temporal lobe, after which he reported face recognition difficulties, especially for people who look similar. The craniotomy also produced a temporary left-superior quadrantanopia, but a recent test showed that his general visual abilities were in the normal range. Despite his prosopagnosia, Galen performed normally when discriminating between exemplars of cars, hairstyles, abstract paintings, and human bodies.

Faith

Faith is a right-handed woman born in 1963. She works as a teacher. In 2012 Faith had a right occipitotemporal resection for epilepsy. Following resection she noticed severe face recognition deficits and a persistent left-superior quadrantanopia. Faith mentioned that she sometimes fails to recognize her own family members. She did not recognize the face of the first author even after spending 10 hours with him the previous day of testing. Faith also mentioned that she could not tell apart the faces of typical people from those who have Down syndrome. Faith's prosopagnosia affects not only recognition of face identity but also of face expression and gaze discrimination. She performed in the low normal range on various tests of object recognition including cars, hairstyles, and abstract paintings. Her general visual abilities were in the normal range.

Lily

Lily is a right-handed woman born in 1950. She was a health services research administrator. Lily reported difficulties recognizing faces immediately after a surgical procedure to repair an arteriovenous fistula. A postoperative MRI showed that the glue-like substance used to repair the fistula leaked onto an adjacent artery causing a stroke. This stroke lesioned Lily's right ventral visual pathway, and MRI scans indicated that her lesions have disrupted the integrity of the right fusiform gyrus. Despite her deficits with face identity, she could recognize face expressions normally. Lily also had problems discriminating between exemplars of cars in a memory task but not bodies. BORB scores indicate that her general visual ability is in the normal range.

Kili

Kili is a right-handed woman born in 1961. She was reported as CB2 in Das, Tadin, and Huxlin (2014). Kili has been a freelance writer for 15 years. Her prosopagnosia was caused by right occipital lobe infarction. She said she was never great with faces and names, but after the stroke she reported difficulties recognizing family members and good friends in the absence of other cues. In her own words: "Faces are often smudged, as though they are standing on the other side of glass shower door. I can see a nose, eyes and mouth, but they don't come together to make a face I can recognize." Kili suffered from a complete left hemianopia after the stroke as examined using the Humprey visual field perimetry (see Figure 1 in Das et al., 2014). She still reported several scotomas in her left peripheral vision when we tested her. Kili had problems recognizing not just face identity, but also face expression and some nonface objects. She was impaired on old–new discrimination tests for houses, cars, and horses. Her general visual ability as examined using BORB was in the normal range except for length matching, suggesting that her visual recognition deficits likely stem from broader abnormalities in higher level processes.

2.2. *Control participants*

Control data were collected from two groups: an older group of 12 individuals (8 female, age range 56–66 years, $M = 62.3$ years, $SD = 3.1$ years) and a younger group of 14 individuals (9 female, age range = 20–33 years, $M = 23.2$ years, $SD = 4.1$ years). Older controls were tested in the UK via a participant panel at the University of Swansea. They were college educated and worked in the university. Eight younger controls were students of Dartmouth College in the United States; six were students from the Universities of Swansea and Aberystwyth in the UK. All controls were native English speakers.

All but one of the older controls completed a 20-question multiple-choice vocabulary test (Hartshorne & Germine, 2015). This is to ensure that their knowledge of words is comparable to those of the older prosopagnosics because vocabulary size might vary more in late adulthood, which in turn could affect word recognition and reading abilities. Words were presented visually using the web-based survey programme Google Forms. Mean accuracy of the older controls ($M = 87\%$, $SD = 11\%$) is not different from mean accuracy of the older prosopagnosics ($M = 90\%$, $SD = 8\%$), $t(13) = 0.52$, $p = .61$. These accuracies are also similar to norms collected from 1608 adults aged 50–64 years ($M = 85\%$, $SD = 13\%$). This analysis indicates that controls and prosopagnosics possess similar vocabulary size that is in the normal range.

2.3. *Tasks, stimuli, and procedure*

Experimental details for all tasks are outlined below. The seven tasks were administered in random order for each participant.

2.3.1. *Lexical decision task: Frequency × Age of Acquisition (AoA)*

2.3.1.1. *Stimuli.* Stimuli were 160 words and 160 nonwords. The 160 words consisted of 80 high-frequency words and 80 low-frequency words (using the CELEX database; Baayen, Piepenbrock, & Van Rijn, 1993). For each frequency set, 40 words were early acquired, and 40 were late acquired (using the Bristol Norms, Stadthagen-Gonzalez & Davis, 2006). Thus word frequency and age of acquisition were manipulated, leading to four orthogonal groups of stimuli each with 40 items: high-frequency early age of acquisition (AoA), high-frequency late AoA, low-frequency early AoA, low-frequency late AoA. Across the four groups, words were matched in terms of length (in letters), mean bigram frequency, and number of orthographic neighbours.

The 160 nonwords were generated by the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002). Nonwords were split into four groups and were matched with the word stimuli for string length, bigram frequency, and orthographic neighbours.

2.3.1.2. *Procedure*. The experiment began with 12 practice trials (6 words and 6 nonwords), which were not repeated as experimental stimuli. Participants were then presented with a total of 320 letter strings (160 words and 160 nonwords) and indicated whether or not each letter string was a word. Stimuli presentation was randomized and controlled using SuperLab Pro. All stimuli were presented in lower-case, Arial font, size 24 point. Words appeared black against a white background.

Each trial commenced with a fixation cross appearing in the centre of the screen for 2000 ms. Target items were then presented at fixation. Items remained on screen until participants made a response. The participants' task was to decide, as quickly and as accurately as possible, whether the target stimulus was a real word or not. Participants indicated their responses by pressing one of two keys on a keyboard. Immediately after a response was made, an asterisk (*) was lit for

500 ms, following which the fixation cross was presented for 2000 ms as the next trial began.

2.3.2. *Lexical decision task: Length*

Stimuli were 120 words and 120 nonwords. The 120 words were split evenly into sets of 3, 5, or 7 letters in length. Sets were matched for CELEX frequency, bigram frequency, and AoA (Bristol Norms). Given the inverse relationship between word length and *N*, it was not possible to match *N* across length sets: 3-letter words, average 13 neighbours; 5-letter words, average 2.25 neighbours; 7-letter words, average 0.2 neighbours. The 120 nonwords were generated by the ARC Nonword Database. Nonwords were split into three sets, matched in length to the word sets. The procedure was the same as that used for the first lexical decision task (see above).

2.3.3. *Reading aloud task: Frequency × Age of Acquisition (AoA)*

2.3.3.1. *Stimuli*. Stimuli were 160 words, half of which were high frequency, half low frequency (using the CELEX database; Baayen et al., 1993). For both sets, half the words were early acquired and half late acquired (using the Bristol Norms, Stadthagen-Gonzalez & Davis, 2006). Thus, word frequency and age of acquisition were manipulated, leading to four orthogonal groups of stimuli each with 40 items: high frequency early AoA, high frequency late AoA, low frequency early AoA, and low frequency late AoA. Across the four groups, words were matched in terms of length, mean bigram frequency, and number of orthographic neighbours.

2.2.3.2. *Procedure*. The experiment began with six practice trials, which were not repeated later. Participants were then presented with a total of 160 experimental words that they were required to name aloud. Word order was randomized and controlled by SuperLab Pro. All stimuli were presented in lower case, Arial font, size 24. Words appeared black against a white background.

Each trial commenced with a fixation cross in the centre of the screen for 2000 ms. Target items were then presented at fixation. Participants were asked to name each item as quickly and as accurately as possible. Items remained on screen until participants responded. Responses were detected using a SV-1 voice key (Cedrus Software) in the United Kingdom and a portable USB microphone in the United States. As the voice key can be triggered by any vocal sound, participants' responses were also recorded using a digital voice recorder and were checked for accuracy by the second author. Once a participant made a response, an asterisk (*) replaced the target item for 500 ms, and then the fixation cross was presented for 2000 ms as the next trial began.

2.3.4. *Reading aloud task: Length*

Stimuli were 120 words split evenly into sets of 3, 5, or 7 letters in length. Sets were matched for CELEX frequency, bigram frequency, and age of acquisition (Bristol Norms). Given the inverse relationship between word length and *N*, it was not possible to match *N* across length sets. The average number of neighbouring words for 3-letter words was 13, for 5-letter words it was 2.25, and for 7-letter words it was 0.2. Procedure was the same as that outlined for the previous task (Section 2.3.3).

2.3.5. *Reading aloud task: Average confusability*

Stimuli were 120 words with six practice trials. Words were matched on *N*, frequency, and average letter confusability. Stimuli were the same as those used by Fiset, Arguin, Bub, Humphreys, and Riddoch (2005). Procedure was the same as that outlined for Section 2.3.3.

2.3.6. *Reading aloud task: Summed confusability*

Stimuli were 120 words taken from Fiset et al. (2005). Words were matched on *N*, frequency, and summed letter confusability. There were six practice trials. Procedure was the same as that outlined for Section 2.3.3.

2.3.7. *Reading aloud task:* N *confusability*

Stimuli were 200 words taken from Arguin and Bub (2005), manipulated for letter confusability and *N*. The 200 four-letter words consisted of 50 that were high confusability high *N*, 50 that were high confusability low *N*, 50 that were low confusability high *N*, and 50 that were low confusability low *N*. There were 10 practice trials. Procedure was the same as that outlined for Section 2.3.3.

2.4. *Statistical analysis*

Based on their age, patients Herschel (57 years old), Lily (64 years old), Faith (50 years old), and Kili (52 years old) were compared to the older controls, while Galen (31 years old) was compared to the younger controls. We used the Crawford's *t* test for single-case analysis (Crawford & Howell, 1998) to compare performances of individual patients to those of controls. We used one-tailed tests throughout because we predicted the presence of deficits a priori. For the older patients, a one-tailed test at .05 level with 11 degrees of freedom results in a critical *t*-value of 1.796; thus performance below 1.796 standard deviations of the control mean was considered abnormal. For the younger patient Galen, a one-tailed test at .05 level with 13 degrees of freedom results in a one-tailed critical *t*-value of 1.771; thus performance below 1.771 standard deviations of the control mean was considered abnormal. For each patient there were a total of 56 statistical comparisons across the seven tasks and across two measures of error and response time. Response times longer than 2.5 standard deviations in a given condition were considered outliers and were thus removed.

3. Results

3.1. *Lexical decision task: Frequency × Age of Acquisition (AoA)*

Figure 2 presents the results for the lexical decision task that varied frequency and age of acquisition. All prosopagnosics performed within the normal range except Kili. Kili made more errors than controls for low-frequency words and was abnormally slow in nearly all conditions.

3.2. *Lexical decision task: Length*

Figure 3 shows the results for the lexical decision task in which we varied word length. All prosopagnosics again performed within the normal range for both words and nonwords, with the exception of Kili. Kili made more errors than controls for 7-letter words and was significantly slower than controls for 5- and 7-letter words.

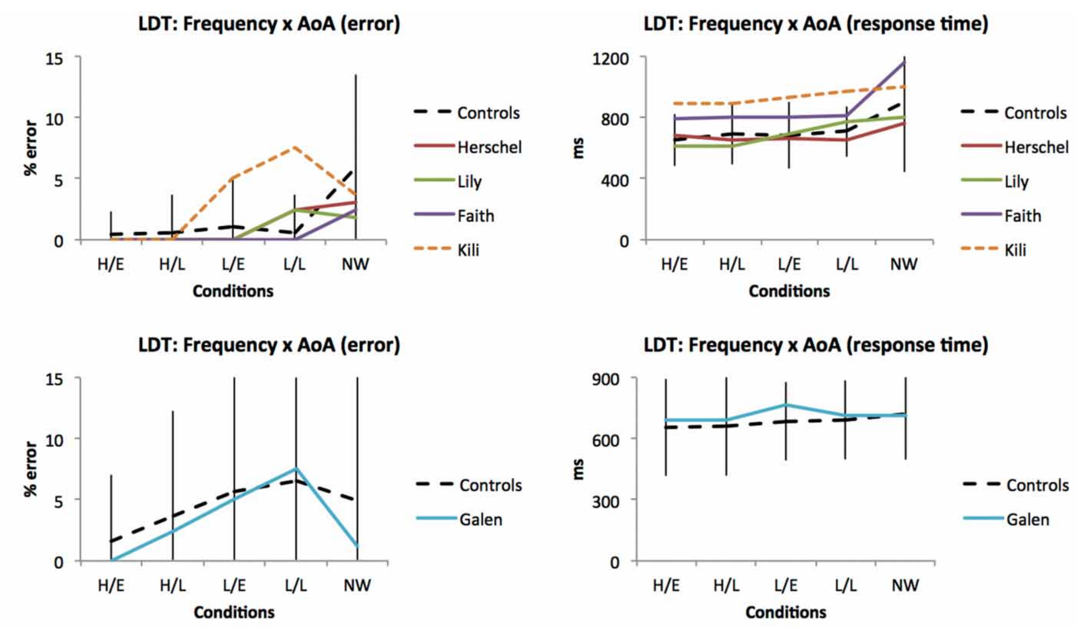
We also assessed the "word-length effect", which is often taken to indicate letter-by-letter reading in pure alexia (Bub, Black, & Howell, 1989). We did this by regressing response time against number of letters to compute slope. Compared to the average of older controls (–3 ms/letter; range = –40 to 25 ms/letter), only Faith (38 ms/letter) exhibited an abnormal slope. The slopes for the other prosopagnosics were in the normal range.

3.3. *Reading aloud task: Frequency × Age of Acquisition*

Figure 4 presents the results for the reading aloud task: frequency versus age of acquisition. Herschel and Faith made more errors than controls for low-frequency/early-acquisition (L/E) words, while Kili did so for the other three conditions: high frequency/early acquisition (H/E), high frequency/late acquisition (H/L), and low frequency/late acquisition (L/L). Kili also read slower than controls for L/E words, and her other response times (RTs), while not significantly abnormal, were in the lower range of controls.

3.4. *Reading aloud task: Length*

Figure 5 presents the results for reading aloud task: length. Only Kili made more errors than controls for 5-letter words, and she was abnormally slow in all conditions. Other prosopagnosics were normal across all conditions. The *t*-values for error performance in the 3-letter condition could not be computed, but all prosopagnosics made zero errors. Regarding the word-length effect, Kili (16 ms/letter) and Lily (23 ms/letter) showed abnormal slopes.



Error	H/E	H/L	L/E	L/L	NW
Herschel	0.4	0.4	0.5	-1.2	0.7
Lily	0.4	0.4	0.5	-1.2	1.0
Faith	0.4	0.4	0.5	0.4	0.9
Galen	0.6	0.3	0.1	-0.2	0.7
Kili	0.4	0.4	**-1.9**	**-4.3**	0.6

RT	H/E	H/L	L/E	L/L	NW
Herschel	-0.3	0.4	0.2	0.7	0.6
Lily	0.5	0.8	-0.1	-0.7	0.4
Faith	-1.5	-1.1	-1.1	-1.2	-1.1
Galen	-0.3	-0.2	-0.8	-0.2	0.1
Kili	**-2.6**	**-1.9**	**-2.2**	**-3.0**	-0.4

Figure 2. Results for lexical decision task (LDT): Frequency × Age of Acquisition (AoA). Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The four word conditions are high frequency/early acquisition (H/E), high frequency/late acquisition (H/L), low frequency/early acquisition (L/E), and low frequency/late acquisition (L/L). The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. [To view this figure in colour, please see the online version of this Journal.]

3.5. *Reading aloud task: Average confusability*

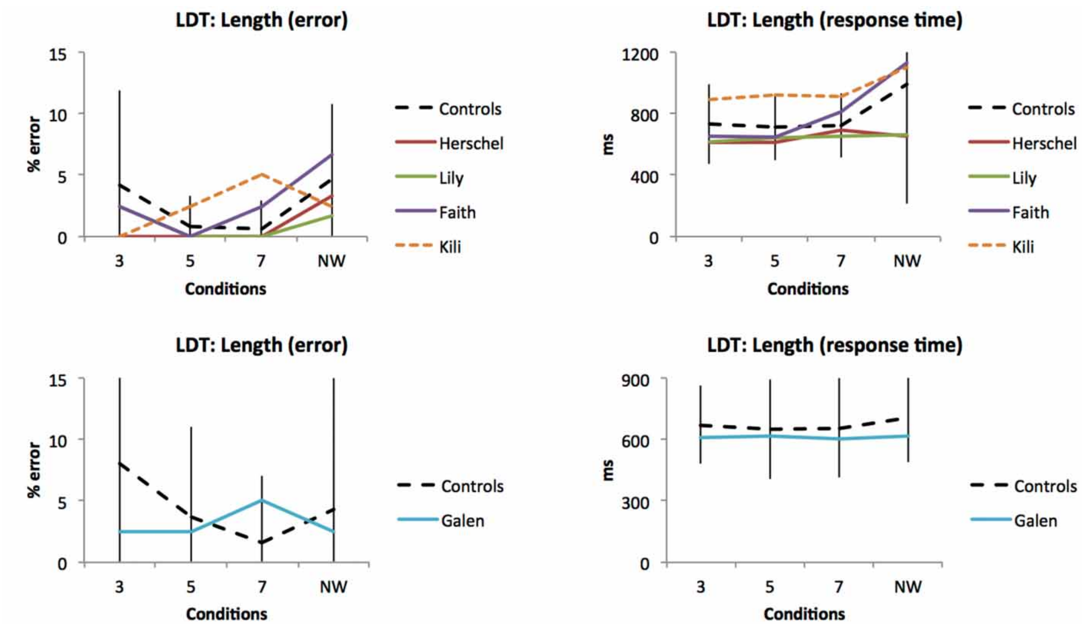
Figure 6 shows the results for reading aloud task: average confusability. All prosopagnosics read normally with the exception of Faith, who made more errors than controls in the 3-letter condition. All prosopagnosics showed normal slopes.

3.6. *Reading aloud task: Summed confusability*

Figure 7 presents the results for reading aloud task: summed confusability. All prosopagnosics read normally except for Herschel in the 5-letter condition, where he made significantly more errors than controls. All prosopagnosics exhibited slopes in the normal range.

3.7. *Reading aloud task: N confusability*

Figure 8 shows the results for reading aloud task: *N* confusability. All prosopagnosics read normally except Kili, who made more errors in the low-*N*/low-confusability (LN/LC) condition and read abnormally slower than controls in almost all conditions.



Error	3	5	7	NW
Herschel	1.0	0.7	0.5	0.4
Lily	0.4	0.7	0.5	0.9
Faith	0.4	0.7	-1.6	-0.6
Galen	0.3	-1.2	0.3	0.3
Kili	1.0	-1.3	**-3.7**	0.7

RT	3	5	7	NW	Slope
Herschel	0.9	0.9	0.2	0.8	-1.3
Lily	0.9	0.6	0.6	0.8	-0.7
Faith	0.6	0.6	-0.8	-0.3	**-2.2**
Galen	0.6	0.3	0.4	0.8	-0.2
Kili	-1.2	**-1.9**	**-1.8**	-0.3	-0.5

Figure 3. Results for lexical decision task: length. Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The three word conditions are words composed of three, five, or seven letters. The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. [To view this figure in colour, please see the online version of this Journal.]

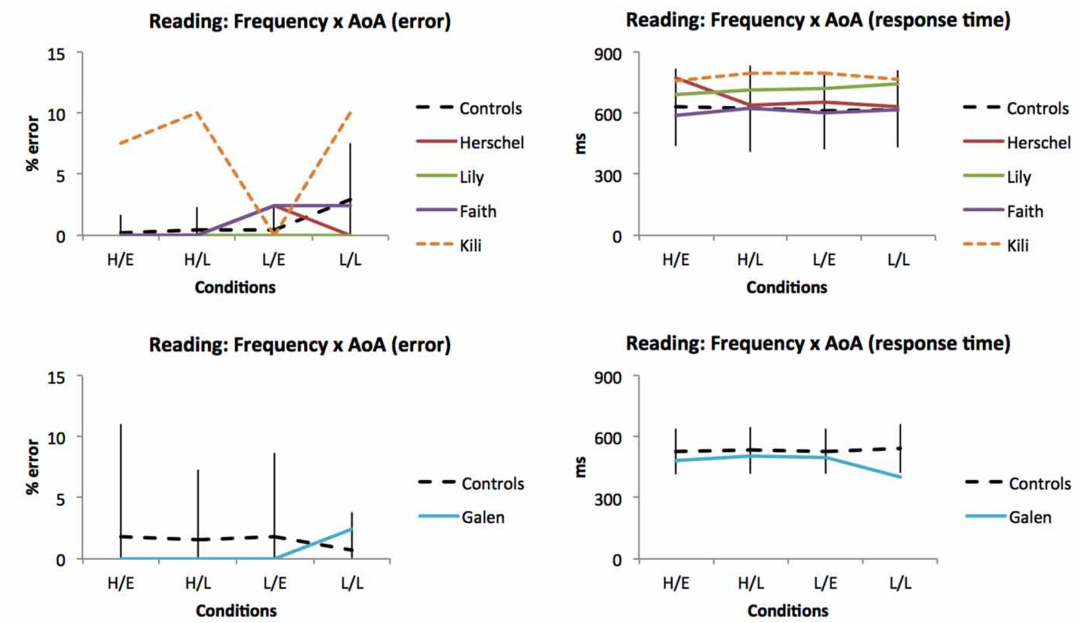
3.8. *Summary of results*

The results can be summarized as follows. Galen was normal across all comparisons. Lily, Herschel, and Faith were each abnormal in one, two, and three comparisons, but this is statistically expected because 56 statistical tests at an alpha of .05 would on average generate 2.8 abnormal results by chance. The exception was Kili who performed worse than controls in 22 comparisons, suggesting word recognition deficits.

In terms of the word-length effect, Faith, Lily, and Kili each showed one abnormal result out of four tests of slopes. It is worth noting, however, that their statistically abnormal slopes (range = 16 to –38 ms/letter) are still within the range of those seen in healthy readers (range = –6 to 32 ms/letter, Barton, Hanif, Eklinder Bjornstorm, & Hills, 2014). As a comparison, three prosopagnosics who had word recognition difficulties in Behrmann and Plaut (2014) exhibited an average slope of 159 ms/letter for the lexical decision task and 142 ms/letter for the reading aloud task. Overall, we conclude that Galen, Lily, Herschel, and Faith all had word recognition abilities in the normal range.

4. Discussion

The present study was designed to test the many-to-many theory of visual object recognition (MTMT,



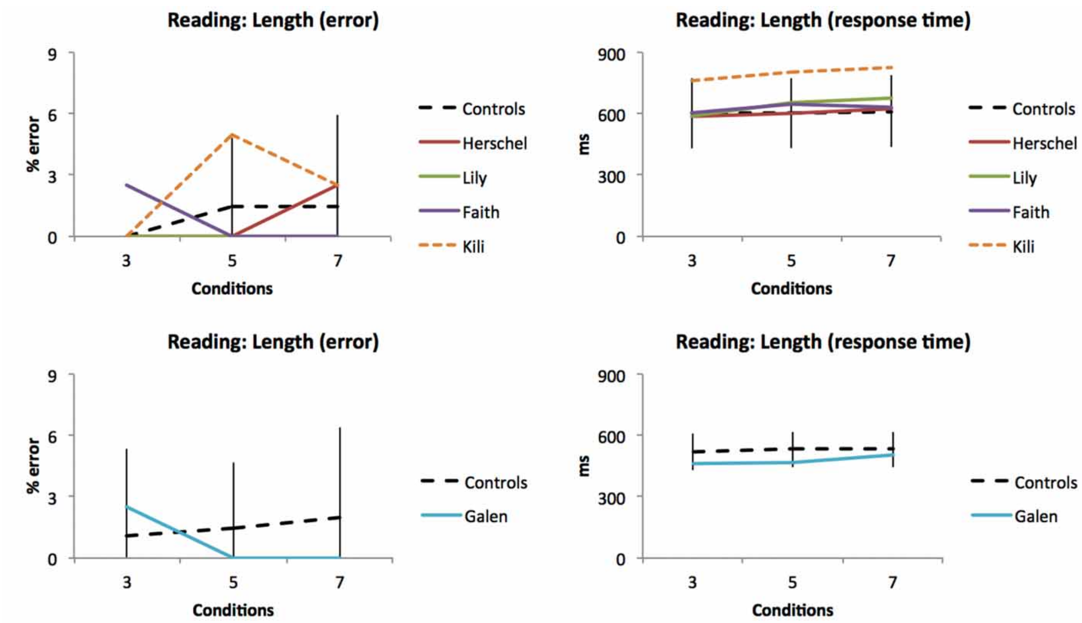
Error	H/E	H/L	L/E	L/L
Herschel	0.3	0.4	**-2.1**	1.2
Lily	0.3	0.4	0.4	1.2
Faith	0.3	0.4	**-2.1**	0.2
Galen	0.4	0.5	0.5	-1.1
Kili	**-9.7**	**-9.5**	0.4	**-2.9**

RT	H/E	H/L	L/E	L/L
Herschel	-1.4	-0.1	-0.4	-0.1
Lily	-0.6	-0.8	-1.1	-1.3
Faith	0.4	0.0	0.1	0.0
Galen	0.7	0.5	0.5	2.2
Kili	-1.3	-1.6	**-1.9**	-1.5

Figure 4. Results for reading aloud task: Frequency × Age of Acquisition (AoA). Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The four conditions are words of high frequency/early acquisition (H/E), high frequency/late acquisition (H/L), low frequency/early acquisition (L/E), and low frequency/late acquisition (L/L). The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. [To view this figure in colour, please see the online version of this Journal.]

Behrmann & Plaut, 2013, 2014). According to MTMT, face and word recognition are carried out by common mechanisms, and they do not depend on category-selective mechanisms that can be selectively impaired in brain-damaged patients. We tested one prediction of MTMT, namely that acquired prosopagnosic patients should also present with deficits in recognizing words. We tested five acquired prosopagnosics with seven tasks of word recognition: two lexical decision tasks and five reading aloud tasks totalling more than 1200 trials. While one patient showed signs of word recognition deficits, four patients exhibited word recognition ability that was not different from those of controls. Inconsistent with MTMT, our study demonstrates that word recognition *can* be normal in acquired prosopagnosia.

Our findings agree with a substantial body of behavioural and neural evidence indicating that face recognition is carried out by mechanisms specialized for processing faces (McKone, Kanwisher, & Duchaine, 2007; McKone & Robbins, 2011). The idea that face recognition relies on face-specific processes has been one of the most debated notions in psychology and cognitive neuroscience. Many lines of evidence have accumulated over the years in support of the existence of specialized face mechanisms, from single-cell data in



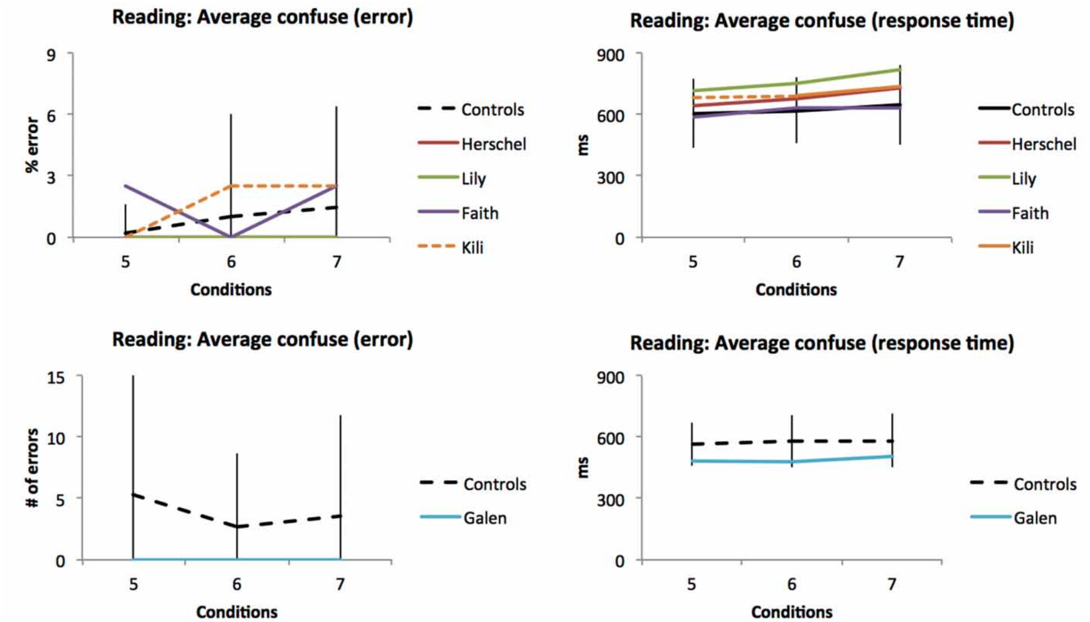
Error	3	5	7
Herschel	n/a	0.8	-0.4
Lily	n/a	0.8	0.6
Faith	n/a	0.8	0.6
Galen	-0.6	0.9	0.9
Kili	n/a	**-2.0**	-0.4

RT	3	5	7	Slope
Herschel	0.2	0.0	-0.2	-1.3
Lily	0.2	-0.5	-0.8	**-3.2**
Faith	0.0	-0.4	-0.2	-0.7
Galen	1.2	1.4	0.6	-1.7
Kili	**-1.8**	**-2.2**	**-2.4**	**-2.1**

Figure 5. Results for reading aloud task: length. Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The three conditions are words composed of three, five, or seven letters. The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. The *t*-values for four prosopagnosics' error performance in the three-letter condition could not be computed because the older controls had a mean and a standard deviation of zero. [To view this figure in colour, please see the online version of this Journal.]

macaque temporal cortex showing almost exclusive response to faces (Tsao, Freiwald, Tootell, & Livingstone, 2006) to reports of face-specific impairments in acquired prosopagnosic patients (Busigny, Joubert, Felician, Ceccaldi, & Rossion, 2010; Rezlescu et al., 2012; Rossion et al., 2003) and developmental prosopagnosic individuals (Duchaine et al., 2006). Patients Herschel, Lily, Faith, and Galen in the present study thus complement previous reports of prosopagnosia without deficits for other types of visual recognition.

More specifically, our study adds to a long list of reports of dissociations between face and word recognition in brain-damaged patients. In the most comprehensive review to date, Farah (1991) identified 58 cases with dissociations between face and word recognition. Of these cases, 42 presented with prosopagnosia without pure alexia, and 16 exhibited pure alexia without prosopagnosia. As mentioned above, many of the reported patients were not tested rigorously in the putatively nonimpaired domain (Plaut & Behrmann, 2013), although several cases seem to offer compelling evidence. Perhaps the most notable case is patient C.K., who was profoundly alexic and object agnosic (Behrmann et al., 1994) yet demonstrated perfectly normal ability to recognize faces, even after thorough testing of many



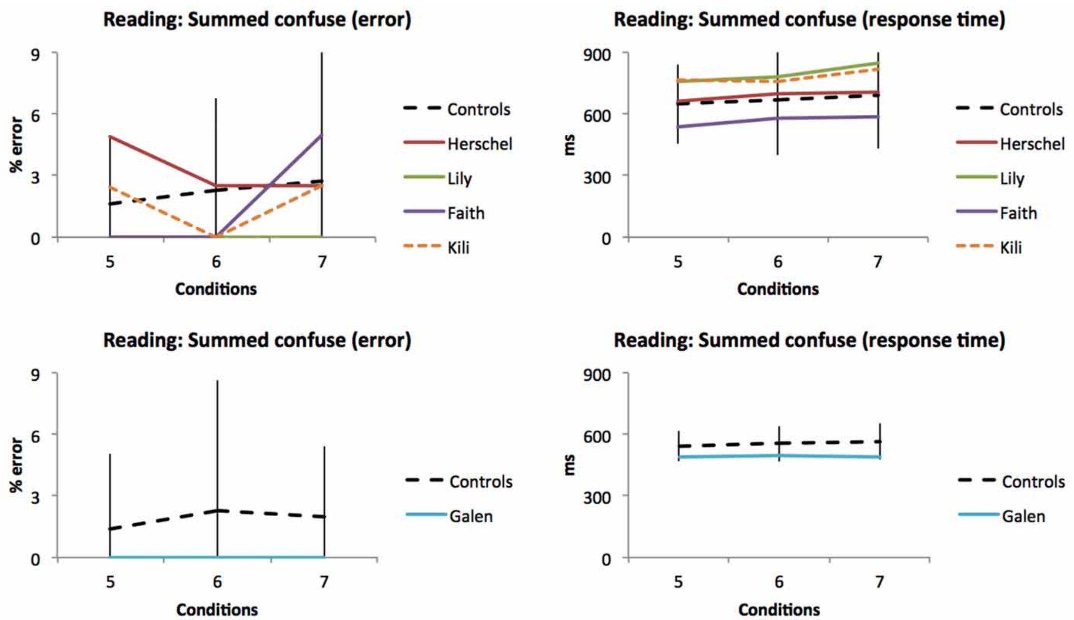
Error	5	6	7
Herschel	0.3	0.4	0.6
Lily	0.3	0.4	0.6
Faith	**-3.1**	0.4	-0.4
Galen	0.8	0.9	0.8
Kili	0.3	-0.6	-0.4

RT	5	6	7	Slope
Herschel	-0.4	-0.7	-0.8	-0.7
Lily	-1.3	-1.5	-1.7	-1.1
Faith	0.2	-0.1	0.2	0.0
Galen	1.4	1.5	1.1	0.0
Kili	-0.9	-0.8	-0.9	-0.2

Figure 6. Results for reading aloud task: average confusability. Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The three conditions are words composed of five, six, or seven letters. The two tables show *t*-values associated with prosopagnosics' performance in the two panels; abnormal *t*-values are in bold. [To view this figure in colour, please see the online version of this Journal.]

aspects of face recognition (Moscovitch et al., 1997).

Our findings of prosopagnosia without word recognition deficits appear to conflict with Behrmann and Plaut's (2014) report of three prosopagnosics with word recognition deficits, which is consistent with MTMT. What explains the discrepancy? One possibility is that the prosopagnosics in Behrmann and Plaut (2014) suffered disruption to both face and word recognition mechanisms, which are independent of one another. On this view, the associated face and word deficits do not support MTMT, because the deficits do not originate from a common source. Another possibility is that the prosopagnosics had problems with more general aspects of vision that contribute to both face and word recognition. In this case, the problems do not result from impairments of face and word mechanisms per se but rather from more generalized visual deficits. All three prosopagnosics seem to fit this latter interpretation: S. M. (Gauthier et al., 1999), C.R. (Gauthier et al., 1999), and R.N. (Marotta et al., 2002) all suffered from severe object agnosia as examined using the Boston Naming Test (Goodglass, Kaplan, & Weintraub, 1983) and Snodgrass and Vanderwart's (1980) line drawings. Their impairments with basic-level recognition suggests that their face and word deficits may originate from earlier visual problems. We would reiterate that this is an



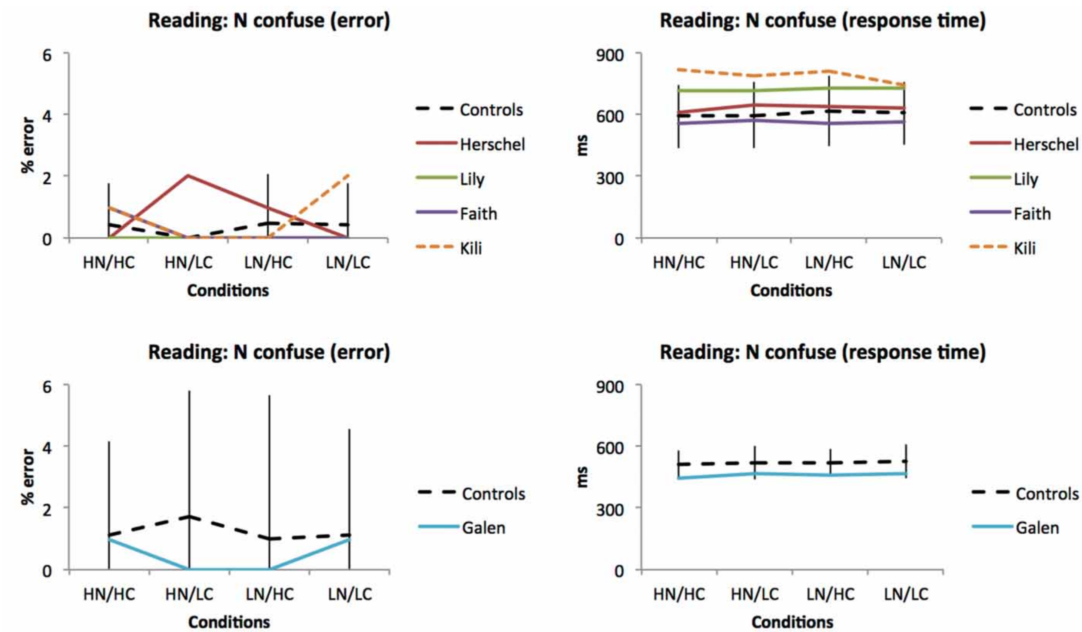
Error	5	6	7
Herschel	**-2.0**	-0.1	0.1
Lily	1.0	1.0	0.8
Faith	1.0	1.0	-0.6
Galen	0.7	0.7	1.1
Kili	-0.5	1.0	0.1

RT	5	6	7	Slope
Herschel	-0.1	-0.2	-0.1	-0.1
Lily	-1.1	-0.8	-1.2	-1.1
Faith	1.1	0.6	0.8	-0.2
Galen	1.5	1.3	1.7	1.0
Kili	-1.2	-0.6	-1.0	-0.2

Figure 7. Results for reading aloud task: summed confusability. Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The three conditions are words composed of five, six, or seven letters. The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. [To view this figure in colour, please see the online version of this Journal.]

example of the danger of interpreting associative data, since co-occurring deficits may be present for many reasons.

It is worth noting that one prosopagnosic, Kili, showed deficits of word recognition. Three points regarding Kili's performance are notable. First, despite being the only case with some word recognition problems, there was no evidence that Kili was more impaired at face processing than the other prosopagnosics (Table 1 shows that her *z*-scores on three face recognition tests were comparable to those of the other patients). In other words, no evidence indicates that the presence or absence of word recognition problems might be connected to severity of face processing impairment (i.e., a continuum of relative impairments as suggested by MTMT). Second, Kili appears to suffer from broader problems of high-level vision, given the presence of impairments discriminating between exemplars of nonface objects including houses, cars, and horses. She also exhibited difficulties in a test of memory for word pairs. No other prosopagnosics showed high-level deficits as broad as Kili's. As a consequence, we would interpret the presence of word recognition problems for Kili in a similar manner to those seen in S.M., C. R., and R.N. discussed earlier. Finally, Kili's difficulties with word recognition might be related to her hemianopia, given the close associations between hemianopia and alexia (Barton et al.,



Error	HN/HC	HN/LC	LN/HC	LN/LC
Herschel	0.6	n/a	-0.6	0.6
Lily	0.6	n/a	0.6	0.6
Faith	-0.8	n/a	0.6	0.6
Galen	-0.5	0.8	0.4	-0.5
Kili	-0.8	n/a	0.6	**-2.2**

RT	HN/HC	HN/LC	LN/HC	LN/LC
Herschel	-0.2	-0.5	-0.2	-0.3
Lily	-1.5	-1.4	-1.2	-1.5
Faith	0.4	0.3	0.7	0.5
Galen	1.8	1.2	1.7	1.4
Kili	**-2.7**	**-2.2**	**-2.1**	-1.6

Figure 8. Results for reading aloud task: *N* confusability. Data are shown in the top left panel (% error) and the top right panel (response time) for older prosopagnosics (in colours) and older controls as a group (black). Middle panels show corresponding data for Galen and the younger controls. Error bars depict ±2 standard deviations of the control mean. The four conditions are words of high *N*/high confusability (HN/HC), high *N*/low confusability (HN/LC), low *N*/high confusability (LN/HC), and low *N*/low confusability (LN/LC). The two tables show *t*-values associated with prosopagnosics' performance in the panels; abnormal *t*-values are in bold. The *t*-values for four prosopagnosics' error performance in the HN/LC condition could not be computed because the older controls had a mean and a standard deviation of zero. [To view this figure in colour, please see the online version of this Journal.]

2014). Consistent with this possibility, her statistically abnormal word-length effect in the reading aloud task: length (16 ms/letter) is within the range of word-length effects generated by simulating left hemianopia (average 31 ms/letter, Sheldon, Abegg, Sekunova, & Barton, 2012).

We did not test another key prediction of MTMT, namely that pure alexia patients should also be impaired, albeit to a lesser extent, in recognizing faces. Our findings thus leave open the possibility that the relationship between mechanisms underlying face and word recognition is asymmetric. That is, while mechanisms that support face recognition do not contribute to word recognition, mechanisms that carry out word recognition may be involved in face recognition. Such an account would predict that while prosopagnosia without word recognition deficits can exist, pure alexia without face recognition deficits cannot. It is important to test this account in future studies, because there is no compelling evidence to date of pure alexia without subtle face recognition deficits. Potential exceptions are patients D.P.T. (Tsapkini & Rapp, 2010) and D.S.N. (Purcell, Shea, & Rapp, 2014), who presented with alexia yet performed normally on two tests of familiar face recognition involving hundreds of trials. Further testing of face recognition with D.P.T. and D.S.N. would be worthwhile.

To sum up, in the present study we found that acquired prosopagnosics can exhibit normal word recognition. Four out of five prosopagnosics that we tested did not show word recognition deficits in seven tests totalling 1200 trials. Our result is inconsistent with a key prediction of the many-to-many theory of object recognition (MTMT), namely that acquired prosopagnosics should present some deficits in recognizing words relative to controls. Rather, our results suggest that face recognition relies on dedicated and dissociable mechanisms from those used for word recognition.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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