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Object recognition in acquired and developmental prosopagnosia

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ABSTRACT

Whether face and object recognition are dissociated in prosopagnosia continues to be debated: a recent review highlighted deficiencies in prior studies regarding the evidence for such a dissociation. Our goal was to study cohorts with acquired and developmental prosopagnosia with a complementary battery of tests of object recognition that address prior limitations, as well as evaluating for residual effects of object expertise. We studied 15 subjects with acquired and 12 subjects with developmental prosopagnosia on three tests: the Old/New Tests, the Cambridge Bicycle Memory Test, and the Expertise-adjusted Test of Car Recognition. Most subjects with developmental prosopagnosia were normal on the Old/New Tests: for acquired prosopagnosia, subjects with occipitotemporal lesions often showed impairments while those with anterior temporal lesions did not. Ten subjects showed a putative classical dissociation between the Cambridge Face and Bicycle Memory Tests, seven of whom had normal reaction times. Both developmental and acquired groups showed reduced car recognition on the expertise-adjusted test, though residual effects of expertise were still evident. Two subjects with developmental prosopagnosia met criteria for normal object recognition across all tests. We conclude that strong evidence for intact object recognition can be found in a few subjects but the majority show deficits, particularly those with the acquired form. Both acquired and developmental forms show residual but reduced object expertise effects.

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Object memory; face; object expertise; cars

Introduction

Is object recognition spared in prosopagnosia? This is a long-standing question that continues to be asked because of its relevance to ongoing debates about the structural and functional basis of object processing in the visual system. One possibility is modular processing, with regions that are wholly dedicated to certain objects (Kanwisher, 2000). Another is distributed processing, with areas that participate in multiple networks that process different object types (Gauthier, Skudlarski, Gore, & Anderson, 2000), most recently exemplified by the many-to-many hypothesis (Behrmann & Plaut, 2013).

It is generally agreed that a diagnosis of prosopagnosia should exclude problems such as mistaking wives for hats (Rossion, 2018a). A problem with object recognition of that severity is more appropriately labelled a general visual agnosia. Rather, the issue is whether, just as a prosopagnosic subject has difficulty recognizing the face of a person, they struggle to identify which hat, or which car or which bird, is before them. This has led to the distinction between "within-category" (i.e., my face, your face) and "between-category" (i.e., face versus hat) recognition (Damasio, Damasio, & van Hoessen, 1982), with the question being whether the former is intact in at least some cases of prosopagnosia. While defining the level of category can be slippery, with multiple potential levels of categorization (e.g., is it "bird" or "hawk" for a red-tailed hawk?) whose suitability may vary with the expertise of the subject, the general point remains that the issue centres on levels of visual identification that are more fine-grained than the broader deficit in general visual agnosia.

Evidence has been marshaled on both sides of the debate. For acquired prosopagnosia, there are many reports of subjects who can still identify members of other natural categories such as birds, dogs, butterflies, flowers, fruit and vegetables (Barton, Cherkasova, Press, Intriligator, & O'Connor, 2004b; Busigny, Graf, Mayer, & Rossion, 2010; Evans, Heggs, Antoun,

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Table 1. Eleven aspects of an ideal comparison between face and object processing.

1. Firm objective diagnosis of prosopagnosia
2. Exclusion of more general visual agnosia or memory problems
3. Tests of object processing probe a similar operational level as the face processing deficit.
4. Test more than two object categories
5. Assess both accuracy and reaction time
6. Object and face tests should have similar task demands
7. Stimulus complexity and/or test difficulty matched between object and face tests
8. Tests of short-term familiarity use different viewpoints to avoid image matching
9. Evaluate strict criteria for putative classical dissociation
10. Comparable decisional space for objects and faces
11. Consider effects of variable subject expertise with objects tested

& Hodges, 1995; Henke, Schweinberger, Grigo, Klos, & Sommer, 1998; McNeil & Warrington, 1993; Riddoch, Johnston, Bracewell, Boutsen, & Humphreys, 2008; Schiltz et al., 2006), and man-made objects such as spectacles, shoes, tools, chairs, lamps, cars and boats (Busigny & Rossion, 2010; Busigny et al., 2010; Farah, Levinson, & Klein, 1995; Henke et al., 1998; Riddoch et al., 2008; Schiltz et al., 2006; Sergent & Signoret, 1992). On the other side, there are subjects with acquired prosopagnosia who have difficulty identifying exemplars of natural objects such as animals, birds, cows, horses, snowflakes, fruits and vegetables (Barton et al., 2004b; Bornstein, 1963; Bornstein, Sroka, & Munitz, 1969; de Haan, Young, & Newcombe, 1991; Gauthier, Behrmann, & Tarr, 1999; Gomori & Hawryluk, 1984; Henke et al., 1998; Newcombe, 1979), and man-made objects such as cars and coins (Bruyer et al., 1983; de Haan et al., 1991; Gomori & Hawryluk, 1984; Henke et al., 1998).

A recent review of the literature on developmental prosopagnosia has made a similar observation, that there appear to be cases of both intact and impaired object recognition (Geskin & Behrmann, 2018). However, the most important outcome of this discussion and the accompanying commentaries was clarifying the limitations of prior reports, which need to be addressed in future studies if we are to make progress on this point. The question "Is object recognition spared in prosopagnosia?" is deceptively simple, and there are numerous conceptual and methodologic complexities that need consideration (Table 1).

First, diagnostic criteria for the presence of impaired face recognition need to be based on objective tests and to be statistically sound (Barton, 2018). This is particularly true for developmental prosopagnosia, which by definition has no obvious lesion and no history of a change in the ability to recognize faces (Barton & Corrow, 2016a). While some protest that not all subjects with prosopagnosic-like complaints meet strict statistical criteria on testing (Zhao et al., 2016), failure to use such criteria carries the risk of including healthy subjects in the study group. Normal object recognition in healthy subjects would be both uninteresting and misleading.

Second, general problems such as visual agnosia or amnesia should be excluded (Barton, 2018). Indeed, some previous subjects reported as prosopagnosic may have had more general processing failures (Behrmann & Plaut, 2014; de Haan & Campbell, 1991; Stollhoff, Jost, Elze, & Kennerknecht, 2010). Impaired object recognition in these subjects may be expected and again is uninteresting.

Third, while there are many ways to assess visual object processing, assessments in prosopagnosia should probe an operational stage that matches that of the face processing deficit (Geskin & Behrmann, 2018). Consider the fact that some prosopagnosic subjects have preserved face discrimination (Dalrymple, Garrido, & Duchaine, 2014): intact object discrimination in these subjects is not evidence of a face-object dissociation.

Fourth, there are many types of objects: how many need to be tested to support a conclusion that object recognition is intact or impaired? While this is akin to asking how many caves need to be searched to confirm that dragons don't exist, an existing claim is that no subject with developmental prosopagnosia who has been tested on more than two object categories has had consistently normal results on all (Geskin & Behrmann, 2018).

Fifth, normal object processing should be shown by both accuracy and reaction times (Geskin & Behrmann, 2018). In theory, speed-accuracy trade-offs may allow some subjects to achieve relatively normal accuracies, possibly by the substitution of alternate but less efficient mechanisms.

Sixth, the general task demands should be equivalent in the object and face tests (Geskin & Behrmann, 2018). For example, if the face test places greater demands on working memory than the object test does, then a working memory deficit may create the false appearance of a face-object dissociation.

Seventh, any dissociation should not simply reflect a difference in stimulus complexity or task difficulty (Campbell & Tanaka, 2018; Geskin & Behrmann,

2018). Concern has been expressed (Geskin & Behrmann, 2018) that some studies used object tests that were too easy (Zhao et al., 2016).

Eighth, if tests of short-term memory for objects are used, they should show different images in the study and test phases. Intact object scores in a test that use the same image throughout may reflect only the ability to process images rather than to recognize objects.

Ninth, evidence for a dissociation must be firm. Failing to fall outside of the performance range of controls may not be definitive proof of normality, particular when the number of control subjects is small (Gerlach, Lissau, & Hildebrandt, 2018). Furthermore, a "putative classical dissociation" requires not only performance within the normal range on one task and outside it on another, but the *difference* in performance should statistically exceed the range of differences seen in controls who have also done both tasks (Crawford, Garthwaite, & Gray, 2003; Gerlach et al., 2018).

Tenth, the decisional space for objects should at least approach that of faces (Ramon, 2018). It is estimated that the average human can recognize about four thousand faces encountered over a lifetime (Jenkins, 2017). Testing with an object category that has only a handful of variants would create another imbalance in the comparison of objects with faces.

Eleventh, the effects of object expertise should be considered (Barton, Hanif, & Ashraf, 2009; de Haan & Campbell, 1991; Sergent & Signoret, 1992). While most humans can be considered face experts, this is not true for almost all other objects, for which people vary in exposure or interest. Performance on object processing tests varies with expertise and this will confound results in prosopagnosic subjects: an average score may actually be poor for an expert, while a low score may be normal for a non-expert. Given existing hypotheses that prosopagnosia may be a problem with expertise processing (Gauthier & Bukach, 2007; Gauthier et al., 2000), a comparison between faces and other objects may not be fair unless object expertise is taken into account.

In this study we attempted to address these points with a study of two prosopagnosic cohorts, with three experiments involving object recognition. As no current test satisfies all the points raised in Table 1, this battery of three tests provides a complementary array as an alternative means of doing so. We addressed points 1 and 2 of Table 1 with objective diagnostic criteria for face recognition impairments and neuropsychological assessments of visual and memory function. As impaired familiarity for faces is the key deficit in all variants of prosopagnosia (Barton & Corrow, 2016a; Dalrymple & Palermo, 2016; Davies-Thompson, Pancaroglu, & Barton, 2014), point 3 is addressed by having all three tests probe either short-term familiarity or long-term identification. We discuss how the remaining points are addressed by our tests in the introductions to each experiment.

Also, given debates about the merits of case studies versus group reports–i.e., the dangers of inferences from a single-case on the one hand, and the potential to obscure dissociations when considering only group means on the other (Behrmann & Geskin, 2018; Geskin & Behrmann, 2018; Rossion, 2018b; Towler & Tree, 2018)–we performed both group and single-subject analyses. Furthermore, we tested both an acquired and a developmental cohort, as the implications of dissociations and associations may differ between these variants, and it is uncertain whether the results for one form generalize to the other (Rossion, 2018b; Starrfelt & Robotham, 2018).

Our first goal was to establish at a group level whether our developmental or acquired prosopagnosic cohorts showed reduced object recognition. By comparing the different tests we aimed to discover which factors may be critical to demonstrating an object processing deficit in prosopagnosia. Our second goal was to examine subjects at an individual level to determine if any met strong criteria for intact object recognition, with normal performance on all three tests (Geskin & Behrmann, 2018). Conversely, we also asked if any subjects were consistently abnormal, not just on one measure, which others would demand as a criterion for impaired object recognition (Garrido, Duchaine, & DeGutis, 2018). Last, given that some consider prosopagnosia a loss of expert visual processing, we evaluated whether expertise effects in object recognition were still evident in the recognition performance of the prosopagnosic cohort.

General methods: the prosopagnosic cohorts

We tested 12 subjects with developmental prosopagnosia (9 female) with a mean age of 41.3 years (s.d. 12.1, range 20–61) (Table 2). These were residents of British Columbia recruited from www.faceblind.org

Table 2. Subject demographic and diagnostic data.

Subject	Age (yrs)	Gender	Etiology	Visual field	CFMT	WRMT Face/50	WRMT Word/50	WRMT Difference	Famous faces (d')
Normative limit					42.1	*	*	10	2.19
Acquired prosopagnosia									
R-IOT1	49	m	vascular malformation	LUQ	44	33	41	8	1.96
R-IOT3	68	m	stroke	LHH	38	33	47	14	0.29
R-IOT4	57	m	stroke	LUQ	27	39	50	11	1.29
L-IOT2	56	m	seizure surgery	full	21	27	42	15	0
B-IOT1	41	m	strokes	LUQ,RUQ	45	28	47	19	2.21
B-IOT2	60	m	trauma/infarct	RHH,LUQ	24	21	42	21	1.31
B-ATOT1	39	f	HSV encephalitis	LUQ	30	27	50	23	0
B-ATOT2	22	f	HSV encephalitis	full	24	19	39	20	−0.15
B-ATOT3	15	m	HSV encephalitis	LHH	28	26	48	22	−0.8
R-AT1	24	f	lobectomy	full	38	17	41	24	1.28
R-AT2	30	f	HSV encephalitis	full	40	27	47	20	0.65
R-AT3	37	m	HSV encephalitis	full	31	29	45	16	0.9
R-AT5	61	f	tumour resection	full	35	28	46	18	1.52
B-AT1	25	m	HSV encephalitis	full	39	23	48	25	−0.36
B-AT2	47	f	trauma, lobectomy	full	31	31	46	15	0.68

Subject	Age yrs	Gender	Old/New Test (faces)	P120	CFMT	WRMT Face/50	WRMT Word/50	WRMT Difference	Famous faces (/60)
Normative limit			2.09	60.5	42.1	*	*	10	45.3
Developmental prosopagnosia									
DP008	61	f	1.46	72	36	36	49	13	43
DP014	42	m	0.67	91	32	30	48	18	8
DP016	52	f	2.06	87	41	37	49	12	37
DP021	31	f	1.78	(–)	37	33	50	17	25
DP024	35	f	1.89	75	41	38	50	12	14
DP033	49	f	2.06	84	29	39	50	11	32
DP035	40	m	1.46	84	36	35	49	14	9
DP038	27	f	1.81	91	39	36	49	13	33
DP039	50	m	1.81	85	22	46	50	4	37
DP044	36	f	2.34	95	40	34	49	15	26
DP201	53	f	3.24	94	42	44	50	6	41
DP202	20	f	−0.21	86	33	32	50	18	(–)

CFMT = Cambridge Face Memory Test, WRMT = Warrington Recognition Memory Test.
HSV = herpes simplex virus.
LUQ = left upper quadrantanopia, RUQ = right upper quadrantanopia, RHH = right hemianopia, m = male, f = female.
(–) not done.
*Criterion varied with age.

who first attended an in-person clinical interview. Diagnostic criteria (Barton & Corrow, 2016a) included, first, self-reported lifelong difficulty in face recognition. In most this was supported by a questionnaire, the 20-item Prosopagnosia Index (Shah, Gaule, Sowden, Bird, & Cook, 2015b)–DP021 did not do the questionnaire because she was evaluated before the creation of this instrument. Second, it required confirmation of impaired face recognition on objective tests. This included (a) a score at least 2 standard deviations below the previously reported control mean on the Cambridge Face Memory Test (Duchaine & Nakayama, 2006), as well as (b) impairment on at least one additional test of face memory with published normative data, which were either (i) a test of famous face identification (Duchaine, Germine, & Nakayama, 2007), (ii) an old/new test of familiarity for recently viewed faces (Duchaine, Wendt, New, & Kulomäki, 2003), or (iii), to meet a criterion for dissociation (Gerlach et al., 2018), a discordance between preserved word memory and impaired face memory on the Warrington Recognition Memory Test (Warrington, 1984) that was in the bottom 5th percentile (i.e., a 10-point difference). All had normal results on Goldmann perimetry and Farnsworth-Munsell 100-hue testing of colour discrimination. All had magnetic resonance imaging with T1-weighted and fluid-attenuated-inversion-recovery (FLAIR) sequences to exclude structural lesions, except for subject DP033 and DP202 for whom magnetic resonance imaging was contraindicated.

We tested 15 subjects with acquired prosopagnosia (6 female) with a mean age of 45.7 years (s.d. 15.9, range 15–71 years). Some were local but many had also been recruited from across North America through www.faceblind.org and flown to Vancouver for study. All had a neuro-ophthalmologic

history and examination, Goldmann perimetry and Farnsworth-Munsell 100-hue testing (Moroz et al., 2016). Six had participated in the initial study of expertise-adjusted car recognition (Barton et al., 2009), and the results of 11 were included in two recent publications (Barton & Corrow, 2016c; Davies-Thompson et al., 2014). All were Caucasian and lived in North America. Diagnostic criteria for acquired prosopagnosia included, first, subjective complaints of impaired face recognition in daily life that began after the neurologic lesion, and second, objective deficits as manifest by impairments on at least two of the following: (a) a test of famous face recognition (Barton, Cherkasova, & O'Connor, 2001), (b) the Cambridge Face Memory test (Duchaine & Nakayama, 2006), (c) the faces component of the Warrington Recognition Memory test (Warrington, 1984) with normal performance on the word component or (d) discordance between preserved word memory and impaired face memory on the Warrington Recognition Memory Test in the bottom 5th percentile.

A final criterion was that all patients with acquired prosopagnosia had a visible lesion on imaging. Thus all had both structural and functional magnetic resonance imaging, as described in prior reports (Hills, Pancaroglu, Duchaine, & Barton, 2015; Pancaroglu et al., 2016). The nomenclature for the acquired prosopagnosic subjects reflects the tissue loss or hypo-intensity on T1-weighted MR images. The anterior tip of the middle fusiform sulcus (Weiner et al., 2014), at the approximate midpoint between the anterior temporal and occipital poles (Talairach $y = -30$), served as a boundary. Lesions mainly anterior to this line were designated as anterior temporal (AT) and those posterior to it as inferior occipitotemporal (IOT). Lesions were more complex in some subjects. FLAIR sequences in R-AT3 had hyperintensities in the left medial temporal lobe and insula. B-ATOT2 had bilateral fusiform lesions and a right anterior temporal lesion, as well as posterior periventricular hyperintensities on FLAIR sequences. B-ATOT3 had mainly right fusiform and anterior temporal lesions, with hyperintensities on FLAIR sequences in the left medial occipitotemporal and occipitoparietal white matter. L-IOT2, who had resection of the left fusiform gyrus for epilepsy, also had atrophy of the right fusiform gyrus and failed to show activation of the right fusiform face area.

Exclusion criteria for both prosopagnosic groups included psychiatric disorders, degenerative disorders of the central nervous system, and best-corrected visual acuity of worse than 20/60. None of our subjects described or showed problems mistaking one type of object for another with real objects or line drawings in the clinical interview, and the possibility of pervasive general perceptual or memory problems was evaluated with a neuropsychological battery (Tables 3 and 4) that included the Wechsler memory scale, third edition (Wechsler, 1997) and the visual object and space perception battery (Warrington & James, 1991): these results have been reported previously for both the developmental (Rubino, Corrow, Duchaine, & Barton, 2016) and acquired cohorts (Hills et al., 2015; Liu, Pancaroglu, Hills, Duchaine, & Barton, 2016). In general, these showed that developmental prosopagnosic subjects have fairly normal performance, with a single low score in a few subjects. In acquired prosopagnosia, despite the fact that no subject displayed clinical evidence of general visual agnosia, there was a wider spectrum of results on the battery, with multiple low scores in a few subjects, particularly those with bilateral occipital lesions, and some subjects performing normally on all tests. To exclude autism spectrum disorders, which can also cause lifelong problems with face recognition (Barton, Hefter, Cherkasova, & Manoach, 2007; Barton et al., 2004a), we required those with developmental prosopagnosia to score less than 32 on the Autism Questionnaire (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001).

The two prosopagnosic groups (Table 2) were comparable in age ($t_{(25)} = 0.13$, $p = 0.90$) and scores on the Cambridge Face Memory Test ($t_{(25)} = 1.01$, $p = 0.32$), but the acquired prosopagnosic cohort had lower scores on the Warrington Recognition Memory Test's face ($t_{(25)} = 4.61$, $p < 0.0001$) and word components ($t_{(25)} = 4.06$, $p = 0.0004$).

The protocol was approved by the Institutional Review Boards of the University of British Columbia and Vancouver Hospital. All subjects gave informed consent in accordance with the principles of the Declaration of Helsinki.

Experiment 1. Old/new tests

This series of tests of short-term familiarity for objects within categories (Duchaine & Nakayama, 2005) has

Table 3. Neuropsychologic test results, acquired prosopagnosia.

Test	Max	R-IOT1	R-IOT3	R-IOT4	L-IOT2	B-IOT1	B-IOT2	B-ATOT1	B-ATOT2	B-ATOT3	R-AT1	R-AT2	R-AT3	R-AT5	B-AT1	B-AT2
Attention																
Trails A (seconds)	–	39	59#	48	54#	32	**80**	24	30	**41**	**39**	21	22	43	18	30
Trails B (seconds)	–	61	**151**	102	117#	**103**	**142**	60	**93**	**114**	61	44	37	78	25	40
Star Cancellation	54	54	54	54	53	54	53	54	54	53	54	54	54	54	54	54
Visual Search	60	54	–	n/a	60	49	56	52	59	56	54	59	59	52	59	56
Memory																
Digit span-forward	16	12	7#	8	10	10	14	12	**7**	10	12	13	16	10	12	9
Spatial span-forward	16	9	6	10	10	5#	8	11	8	8	9	9	12	6	10	9
Word list, immediate recall	48	28	31	37	27	**19**	35	**17**	27	29	28	35	31	24	27	23#
Visuo-perceptual																
Hooper Visual Organization	30	27	27	22	**9**	19.5	22.5	17.5#	**12**	**6.5**	27	28	27.5	22	20	28
Benton Judgment of Line Orientation	30	29	20#	24	23	29	29	26	22	26	29	28	30	21	28	28
Visual Object and Spatial Perception																
Object: Screening	20	20	20	18	20	20	20	20	20	19	20	20	20	17	20	20
Incomplete Letters	20	19	19	19	17	19	19	19	19	**17**	19	20	19	20	19	19
Silhouettes	30	21	22	18	**3**	**9**	**12**	**9**	**4.5**	**2**	21	18	22	19	**10**	25
Object Decision	20	16	19	19	**13**	**9**	**14**	**9**	**10**	**8**	16	20	17	**14**	16	18
Progressive Silhouettes	20	9	**16**	13	10	12	**15**	11	4	**20**	9	10	11	**17**	**17**	8
Spatial: Dot Counting	10	10	9	9	10	10	10	10	9	9	10	10	10	10	10	10
Position Discrimination	20	20	**18**	19	19	19	19	20	**15**	**14**	20	20	19	**18**	19	20
Number Location	10	10	9	10	10	10	10	10	8	**6**	10	9	10	10	10	10
Cube Analysis	10	10	9	10	10	10	10	10	9	–	10	10	10	8	10	9
Imagery																
Mental Rotation	10	10	10	10	7	10	10	10	10	10	10	9	10	10	10	**5**

Bold denotes impaired, # denotes borderline performance.

been used in various iterations in several prior reports on developmental prosopagnosia (Dalrymple et al., 2014; Duchaine et al., 2007; Lee, Duchaine, Wilson, & Nakayama, 2010). It addresses point 4 by having tests for four different types of objects, and point 5 by assessing both A' for object memory and reaction time.

Table 4. Neuropsychologic test results, developmental prosopagnosia.

Test	Max	DP008	DP014	DP016	DP021	DP024	DP033	DP035	DP038	DP039	DP044	DP201	DP202
Attention													
Trails A (seconds)	–	15	16	18	21	11	15	16	20	35	15	24	14
Trails B (seconds)	–	29	35	43	46	20	31	51	65	44	42	40	31
Star Cancellation	54	54	53	52	52	54	52	53	54	53	54	52	54
Visual Search	60	58	56	59	58	59	59	55	60	53	60	59	52
Memory													
Digit span-forward	16	13	13	13	11	12	14	14	11	11	14	11	10
Spatial span-forward	16	8	10	10	6#	10	9	11	10	5#	–	9	8
Word list, immediate recall	48	34	39	29	44	43	42	39	45	31	39	36	31
Visuo-perceptual													
Hooper Visual Organization	30	27	28.5	26	27.5	26.5	28.5	24	24.5	20	26.5	25	29
Benton Judgment of Line Orientation	30	22	30	23	30	24	29	28	23	29	29	24	27
Visual Object and Spatial Perception													
Object: Screening	20	19	20	20	20	20	20	20	19	20	20	20	20
Incomplete Letters	20	20	19	20	19	20	20	20	19	19	19	20	20
Silhouettes	30	20	**14**	20	21	22	21	20	23	21	22	26	22
Object Decision	20	17	19	17	18	18	17	20	19	18	**15**	17	16
Progressive Silhouettes	20	13	8	10	9	6	11	11	11	8	10	11	8
Spatial: Dot Counting	10	10	10	10	10	10	10	9	10	**8**	10	10	10
Position Discrimination	20	**18**	20	20	20	20	20	19	20	20	20	20	20
Number Location	10	9	10	10	10	10	9	10	10	10	10	10	10
Cube Analysis	10												
Imagery													
Mental Rotation	10	7	10	10	9	10	10	10	10	10	10	**5**	9

Bold denotes impaired, # denotes borderline performance.

Methods

Subjects

26 healthy subjects served as controls, 18 female, with mean age of 43.4 years (s.d. 16.4, range 21–71). All 12 subjects with developmental prosopagnosia participated. One of the 15 subjects with acquired prosopagnosia did not (B-ATOT3). Because of time limitations, some of the subjects with acquired prosopagnosia and one subject with developmental prosopagnosia did not perform all four tests.

Procedure

Subjects were tested in a dimly lit room, seated approximately 40 cm from the monitor. Instructions were given both verbally and on the monitor to ensure that subjects understood the procedure.

There were four different object tests, for cars, guns, horses and sunglasses. The cars test showed greyscale images against a white background of automobiles with ornaments removed. All faced the same direction. Compacts, sedans, and trucks were equally represented among the old and new stimuli. Image sizes were adjusted to maintain the proper relation to the other members of the set. The guns test used colour images of handguns with decorations removed. The guns were presented in the same orientation and scaled to approximately equal size. The horses test presented colour photographs of model horses shown in side view. Finally the sunglasses test showed coloured frontal images of sunglasses. We omit results for houses and scenes, which may relate more to perceptual systems for navigation and orientation, and which we reported in a previous study (Corrow et al., 2016).

For each test, a study phase presented subjects with 10 targets sequentially, for 3 s each, and each target shown twice. After the study phase there was a brief pause during which instructions were presented again on the screen. During the recall phase, participants were given 50 trials consisting of a random order of 2 repetitions of each of the 10 targets ("old") and 30 distractors not seen during the study phase ("new"). The images of the targets were the same as those seen during the study phase. Subjects responded whether an image in the recall phase was old or new with a mouse click. The order of the stimuli in the study and recall phases of a block was the same for all subjects.

Analysis

First, the Shapiro–Wilk W test for goodness of fit indicated that the reaction times in the control groups were not normally distributed for guns, horses or sunglasses, but the ln-transformed data were. Hence outcome variables of each subject for each of the four tests were the discriminative index A′ and the ln (mean reaction time). At the group level we compared the three cohorts using ANOVA, with group (control, acquired, developmental) and stimulus type (cars, guns, horses, glasses) as the main factors.

To assess single-subject performance, we obtained 95% prediction intervals (Whitmore, 1986) from the control cohort to classify the scores of prosopagnosic subjects as normal or impaired. To satisfy strict criteria suggested for normal performance (Geskin & Behrmann, 2018), a subject had to have normal A′ and reaction time on all four tests.

On the other hand, the criteria for impairment have been debated, with concerns that too liberal criteria – e.g., falling below two standard deviations on even just one of eight measures – would have resulted in erroneous classification of a third of 18 control subjects in one study as having object processing difficulties (Garrido et al., 2009, 2018). In our cohort of 26 controls, five had at least one A′ or reaction time measure that fell outside the 95% prediction interval, which corresponds to 2.1 standard deviations. No control subject had an abnormal A′ or reaction time on more than one test. Hence we used a criteria for poor object recognition as abnormalities on at least two of the four tests, with one of those abnormalities having to be a low A′. Subjects who did not meet the stringent criteria for normal performance or those for abnormal performance we considered to lie in a "grey zone".

Results

i. Group analysis

For A′, there was an effect of group ($F_{(2,43)} = 8.66$, $p < 0.0007$): Tukey's HSD test showed that the group with acquired prosopagnosia had lower A′ than either the controls or those with developmental prosopagnosia, but the latter two did not differ from each other (Figure 1A). There was an effect of stimulus type ($F_{(3,125)} = 4.29$, $p < 0.006$): Tukey's HSD test showed that guns had lower A′ than either cars and horses. However, there was no interaction between group and stimulus type ($F_{(6,125)} = 1.11$, $p = 0.36$).

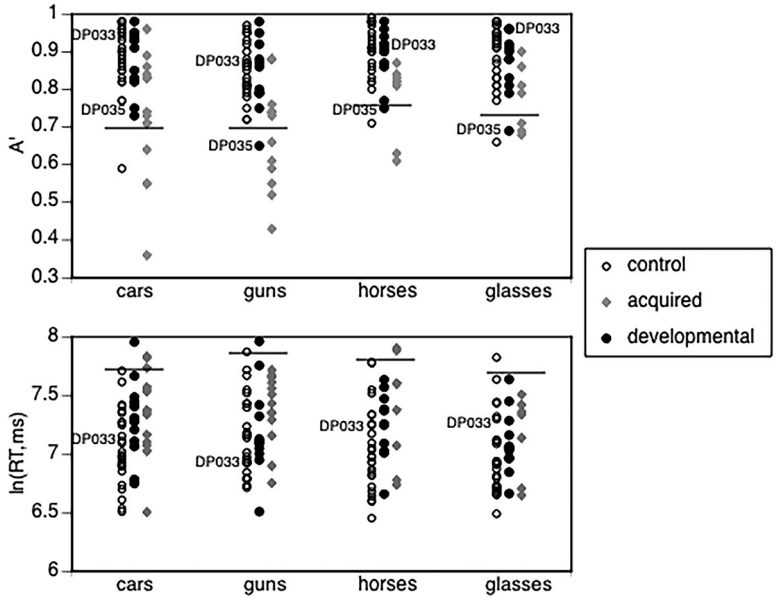

Figure 1. Results, Old/New Tests. A′ (top graph) and ln(reaction time) (bottom graph) are shown for each of the four tests, using cars, guns, horses and glasses as stimuli, with individual results shown for subjects in each of the three groups (control, acquired prosopagnosia, developmental prosopagnosia). Horizontal dashes indicate 95% prediction limits: A′ below those lines or ln(reaction time) above them are considered abnormal. We flag the A′ results for DP035, the only developmental prosopagnosic who met criteria for abnormal object recognition on this test. and the A′ and reaction times of DP033.

For reaction time (Figure 1B), there was an effect of group ($F_{(2,51)} = 4.32$, $p < 0.019$). Again, Tukey's HSD test showed that the group with acquired prosopagnosia had slower reaction times than the controls but those with developmental prosopagnosia did not differ from either the controls or those with acquired prosopagnosia. There was an effect of stimulus type ($F_{(3,133)} = 6.54$, $p < 0.0004$): Tukey's HSD test showed that responses to sunglasses had faster reaction times than those for the other three categories. There was no interaction between group and stimulus type ($F_{(6,133)} = 1.07$, $p = 0.38$).

We examined whether there was a correlation between object and face processing in prosopagnosic subjects, using the Cambridge Face Memory Test scores and the average of the scores for cars and guns, for which we had the most comprehensive data. Given that correlations have greater power and are more stable for larger sample sizes we combined both prosopagnosic cohorts (Schonbrodt & Perugini, 2013). There was no correlation with either A′ ($r = 0.09$, $F_{(1,24)} = 0.18$, $p = 0.67$) or reaction time ($r = 0.23$, $F_{(1,24)} = 1.29$, $p = 0.27$). Among our control subjects, 19 had also done the Cambridge Face Memory Test, and these also showed a lack of correlation with A′ ($r = 0.11$, $F_{(1,18)} = 0.22$, $p = 0.64$) or reaction time ($r = 0.31$, $F_{(1,18)} = 2.05$, $p = 0.17$) for car and guns.

ii. Single-subject analysis

Eight of the 12 subjects with developmental prosopagnosia performed in the normal range for both A′ and reaction time on all four categories (Figure 1, Table 5). One subject met our criterion for poor object recognition: DP035 had low A′ on three of the four categories, sparing only cars, while his reaction times were above the control means, implying that this was not a speed-accuracy trade-off. DP014 had increased reaction times on three of the four categories, sparing only horses, but normal A′ measures. Because two control subjects showed a similar general increase in reaction times, we did not consider DP014's results as definitive proof of impaired object recognition.

Among the 14 subjects with acquired prosopagnosia, three performed in the normal range for A′ and reaction time on all four categories. These were subjects R-AT1, R-AT2 and B-AT2, and hence all with anterior temporal damage. Five met our criterion for poor object recognition: R-IOT3, B-IOT2, L-IOT1, B-ATOT1, and B-ATOT2. Thus, all the latter had occipitotemporal damage, frequently bilateral.

Experiment 2. Cambridge bicycle memory test

This test (Dalrymple et al., 2014) mimics the method and format of the Cambridge Face Memory Test.

Table 5. Results of Old/New Tests.

	Cars		Guns		Horses		Glasses	
Subject	A′	RTs	A′	RTs	A′	RTs	A′	RTs
Controls								
Mean	0.89	1220	0.86	1336	0.91	1215	0.89	1138
s.d.	*0.09*	*395*	*0.07*	*491*	*0.07*	*476*	*0.08*	*445*
95% PI	0.70	2049	0.70	2366	0.76	2214	0.73	2071
Acquired prosopagnosia								
Mean	0.73	1656	0.69	1700	0.78	1731	0.78	1349
s.d.	*0.16*	*546*	*0.14*	*438*	*0.10*	*735*	*0.09*	*416*
R-IOT1	0.71	1869	0.76	1469				
*R-IOT3**	*0.36*	*1595*	*0.52*	*2244*				
R-IOT4	0.84	2518	0.88	2150	0.81	1993		
*L-IOT1**	*0.73*	*1904*	*0.55*	*1562*	*0.63*	*2704*	*0.69*	*1572*
B-IOT1	0.89	1938	0.74	1821	0.61	2655	0.79	1821
*B-IOT2**	*0.64*	*2286*	*0.74*	*1915*	*0.82*	*2005*	*0.71*	*1669*
*B-ATOT1**	*0.55*	*1568*	*0.61*	*2107*				
*B-ATOT2**	*0.55*	*2494*	*0.59*	*2018*				
R-AT1	**0.83**	**668**	**0.74**	**856**	**0.87**	**877**	**0.81**	**771**
R-AT2	**0.96**	**1537**	**0.88**	**2136**	**0.84**	**1596**	**0.90**	**1537**
R-AT3	0.83	1179	0.88	1555	0.83	1177	0.68	1258
R-AT5	0.71	1292	0.43	1283				
B-AT1	0.86	1213	0.66	1688				
B-AT2	**0.74**	**1125**	**0.73**	**991**	**0.82**	**844**	**0.86**	**816**
Developmental prosopagnosia								
Mean	0.88	1544	0.84	1455	0.89	1453	0.87	1257
s.d.	*0.08*	*552*	*0.10*	*631*	*0.07*	*387*	*0.08*	*369*
DP008	**0.93**	**1643**	**0.79**	**1152**	**0.87**	**1106**	**0.88**	**1153**
DP014	0.95	2849	0.95	2868	0.96	2068	0.92	2071
DP016	0.94	2136	0.86	2334	0.86	1402	0.81	1130
DP021	0.83	1783						
DP024	**0.91**	**1707**	**0.98**	**1514**	**0.98**	**1608**	**0.96**	**1056**
DP033	**0.95**	**1224**	**0.88**	**1043**	**0.91**	**1416**	**0.96**	**1458**
*DP035**	*0.75*	*1350*	*0.65*	*1667*	*0.75*	*1758*	*0.69*	*1170*
DP038	**0.82**	**853**	**0.79**	**671**	**0.77**	**779**	**0.79**	**782**
DP039	**0.93**	**1492**	**0.87**	**1198**	**0.92**	**1586**	**0.88**	**1061**
DP044	**0.98**	**1169**	**0.75**	**1246**	**0.92**	**1125**	**0.90**	**1288**
DP201	**0.85**	**1444**	**0.92**	**1218**	**0.94**	**1939**	**0.91**	**1720**
DP202	**0.73**	**882**	**0.80**	**1100**	**0.90**	**1199**	**0.83**	**939**

Underline = abnormal test results.
Bold = subjects with all normal scores, * = subjects impaired by criteria.

Hence it addresses point 6, that a non-face object test should have the same task demands as the face test used (Geskin & Behrmann, 2018). While it can be challenging to equate stimulus complexity across large stimulus sets, by the results for accuracy the Cambridge Bicycle and Face Memory Tests are at least comparable in level of difficulty (Biotti et al., 2017). Indeed, our control data below showed that if anything the bicycle test was slightly more difficult. This addresses point 7, that an appearance of normal object recognition can be created when object tests are too easy (Campbell & Tanaka, 2018; Geskin & Behrmann, 2018). Also, the "novel images" component of the test addresses point 8, that tests of short-term familiarity should show different pictures of the same objects in the learning and testing phases, to reduce the possible use of low-level image matching by the subject, a weakness of the Old/New Tests. For this test we had 140 control subjects, which addresses point 9 regarding the quality of evidence for dissociation. Failure to show abnormal scores on tests of object recognition may not be strong proof of normality when the number of controls is small and the possibility of a type II error is high (Gerlach et al., 2018). Also, since both prosopagnosic and control subjects were tested on both the Cambridge Bicycle and Face Memory Tests, this allowed us to determine if any subject met the stricter criteria for a "putative classical dissociation", with a difference between the two test scores that is also significantly different from the controls (Crawford et al., 2003; Gerlach et al., 2018). Finally, although reporting of the various Cambridge Memory Tests often does not include reaction time, we collected and analyzed these data as well, addressing point 5.

Compared to the Cambridge Car Memory Test (Dennett et al., 2012), which is constructed along similar lines, the Cambridge Bicycle Memory Test may have better diagnostic properties. In one study that included both, control scores on the bicycle test were more similar to those on the Cambridge Face Memory Test than were the scores on the car test (Biotti & Cook, 2016). Also, while some studies find reasonable control performance on the car test (Dennett et al., 2012; Esins, Schultz, Stemper, Kennerknecht, & Bulthoff, 2016; Gerlach, Klargaard, & Starrfelt, 2016), in others (Biotti & Cook, 2016; Biotti et al., 2017) the 95% prediction intervals overlap chance performance, making it impossible to classify a single subject as abnormal.

Methods

Subjects

Controls were 139 subjects (95 female), 73 of whom performed the test in a laboratory, and 66 online, of a similar age range to our prosopagnosic subjects (18–64 years, mean 27.0, s.d. 9.8). All 12 subjects with developmental prosopagnosia participated, performing the test in the laboratory. As this test was developed after we had evaluated the acquired prosopagnosic cohort, these subjects were contacted by email and asked to perform the test online. Ten of the original 15 subjects were able to participate. Two had died since the study began (B-IOT1, R-AT5), and three could not be contacted or did not respond to our request.

Protocol

This test of object memory (Dalrymple et al., 2014) was designed to mirror the protocol of the Cambridge Face Memory Test, which has been described in detail elsewhere (Duchaine & Nakayama, 2006). Subjects study the images of six bicycles, in side and two three-quarter views with each view presented for three seconds. In the 18 trials of the "introductory" phase, subjects are shown one of these three studied images with two distractors and indicated which of the three was an image seen in the study phase. In the "novel images" phase, the target bicycle images are views of one of the six studied bicycles that differ in viewpoint or lighting, and again are paired in each trial with two distractor images. This has 30 trials. The third, "novel images with noise" phase, is similar to the second phase, except that Gaussian noise has been added to the images, and consists of 24 trials. Immediately before both the 'second and third phases participants are presented with a review image that shows a side picture of each of the six target bicycles for 20 s. Because of evidence that the "novel images with noise" phase does not improve the diagnostic performance of the Cambridge Face Memory Test (Corrow, Albonico, & Barton, 2018), the third phase was not administered to the controls or those with acquired prosopagnosia.

In addition to this methodologic similarity, the images of faces and bicycles in the study phase both span about 7.5° of viewing angle at 57 cm viewing distance, while in the test phase the bicycles span about 19° and the faces 21.5°.

Analysis

We limited our comparison between the Cambridge Face and Bicycle Memory Tests to the first two (introductory and novel images) phases, with scores out of 48. Our preliminary analyses of the control data used these raw scores for accuracy. The Shapiro–Wilk W test for normality indicated that the reaction times in the control groups were not normally distributed for either the face ($W = 0.93$, $p < 0.0001$) or bicycle tests ($W = 0.91$, $p < 0.0001$). Hence we used a log transform of the reaction time data. This gave an improved fit to a normal distribution for the bicycle data, though still slightly skewed ($W = 0.97$, $p < 0.01$); for the face data it allowed us not to reject the null hypothesis that the samples were distributed normally ($W = 0.99$, $p = 0.92$).

For the control data, we first examined the effect of age on scores. The correlation between age and accuracy was significant for the Cambridge Face Memory Test ($r = 0.40$, $F_{(1,138)} = 27.2$, $p < 0.0001$) but not the Cambridge Bicycle Memory Test ($r = 0.12$, $F_{(1,138)} = 2.26$, $p = 0.13$). To control for the effect of age, we used the large data set of the control subjects to perform an age-adjustment of the raw accuracy scores for both tests, by regressing out the variance due to age (Corrow et al., 2018; Liu et al., 2016). We calculated the slope of the regression of scores versus age in the overall control group. Using this regression we then determined the age-predicted score for each prosopagnosic and control subject. In a typical non-adjusted analysis, the deviation of any subject's result is the difference between their result and the mean of the control group, and their variance is the square of that deviation. In our age-adjusted analysis, their deviation is the difference between their result

Table 6. Results of Cambridge Bicycle and Face Memory Tests, group level.

	Number	Accuracy (/48)*		Log (reaction time, ms)*	
		Mean	s.d.	Mean	s.d.
Cambridge Face Memory Test					
Laboratory controls	73	39.90	5.88	3.48	0.12
Online controls	66	40.32	4.75	3.45	0.16
(Pooled controls	*139*	*40.09*	*5.35*	*3.46*	*0.14)*
Developmental prosopagnosia	12	23.48	5.73	3.87	0.24
Acquired prosopagnosia	10	18.88	6.18	3.80	0.14
Cambridge Bicycle Memory Test					
Laboratory controls	73	37.70	4.81	3.47	0.17
Online controls	66	36.59	7.11	3.40	0.20
(Pooled controls:	*139*	*37.17*	*6.02*	*3.44*	*0.19)*
Developmental prosopagnosia	12	38.90	3.80	3.68	0.15
Acquired prosopagnosia	10	33.10	7.40	3.86	0.19

*Age-adjusted data.

and their age-predicted score. One could then simply report these deviations between real and predicted values as their age-adjusted score, in which case the mean of the deviations in the control group would be zero. To create an age-adjusted score comparable in magnitude to the raw score we arbitrarily added the mean of the control group to each subject's deviation.[1] The result is that the mean of the deviations in the control group equals the mean of the raw scores.

For the group analysis we then compared age-adjusted scores using an ANOVA with group (acquired prosopagnosia, developmental prosopagnosia, lab control, online control), test (Bicycle, Face) and gender as factors. A similar analysis was performed for age-adjusted log reaction times.

For the single-subject analysis, we calculated 95% prediction limits for age-adjusted performance on the Cambridge Face and Bicycle Memory Tests as well as 95% prediction limits for the difference between the face and bicycle Tests. To meet strict criteria for a putative classical dissociation (Gerlach et al., 2018), a subject with developmental prosopagnosia had to have a) a bicycle score within the normal range, b) a face score in the abnormal range, and c) a bicycle-face difference outside of the normal range. This analysis was done for both accuracy and log reaction time.

This method follows a logic similar to that (Crawford & Garthwaite, 2007) advocated for using regression equations derived from summary data–means, standard deviations, and correlation coefficients–to allow comparison of single subjects against "continuous norms" (Zachary & Gorsuch, 1985) across the age spectrum, rather than against discrete norms for arbitrarily defined age bands. As a second method of evaluating for dissociations in the presence of variations in performance related to age, we used a Bayesian standardized differences test allowing for covariates (Crawford, Garthwaite, & Ryan, 2011), with the BSDT_Cov_Raw.exe programme (https://homepages.abdn.ac.uk/j.crawford/pages/dept/SingleCaseMethodsComputerPrograms.HTM).

Results

i. Control analysis

The Cambridge Bicycle Memory Test had a comparable level of difficulty to the Cambridge Face Memory Test. In fact, the Cambridge Bicycle Memory Test was slightly harder, with mean accuracy of 37.17 (s.d. 6.07), compared to 40.08 (s.d. 5.86) out of 48 for the Cambridge Face Memory Test. The within-subject paired difference of −2.91 (s.d. 7.41) was significant ($t_{(138)} = 4.64$, $p < 0.0001$) due to the large number of subjects. There was a significant correlation between the scores on the bicycle and the face tests ($r = 0.23$, $F_{(1,138)} = 7.58$, $p < 0.007$). Both tests showed good reliability, with Cronbach's alpha of 0.84 for the Cambridge Face Memory Test and 0.81 for the Cambridge Bicycle Memory Test. For comparison, Cronbach's alpha has been calculated at 0.84 for the Cambridge Car Memory Test (Dennett et al., 2012).

Reaction times for the Cambridge Bicycle Memory Test (mean 2735 ms) were slightly faster than those for the Cambridge Face Memory Test (mean 2909 ms) in our controls ($t_{(138)} = 2.00$, $p = 0.047$). Log reaction times were correlated between the two tests ($r = 0.57$, $F_{(1,138)} = 65.37$, $p < 0.0001$).

ii. Group analysis

For age-adjusted accuracy (Table 6), there was a group effect ($F_{(3,160)} = 30.22$, $p < 0.0001$) and a test effect ($F_{(1,160)} = 51.70$, $p < 0.0001$). More importantly there was an interaction between group and test ($F_{(3,160)} = 35.90$, $p < 0.0001$). Tukey's HSD test showed that, for faces, accuracy was lower for both prosopagnosic cohorts than either of the two control groups, with no difference between the prosopagnosic cohorts or between the control groups. However, for bicycles there was no difference between any group. Within the two prosopagnosic groups scores with bicycles were better than those for faces, while there was no difference between bicycles and faces for the laboratory controls and slightly better scores for faces than

bicycles in the online controls. There were no significant effects involving gender.

For age-adjusted log reaction time (Table 6), there was a group effect ($F_{(3,160)} = 38.97$, $p < 0.0001$) and a test effect ($F_{(1,160)} = 4.87$, $p < 0.03$). There was an interaction between group and test ($F_{(3,160)} = 5.86$, $p < 0.0008$). Tukey's HSD test showed that, for both bicycles and faces, both prosopagnosic groups were slower than either control group, but there was no difference between prosopagnosic groups or between control groups. Within each group, reaction times were similar for faces and bicycles in all groups except for the developmental prosopagnosic cohort, who were faster with faces than bicycles.

The correlation between raw accuracy of the bicycle and face tests in the combined prosopagnosic cohorts ($r = 0.20$) was of a similar magnitude to that of the controls but with the lower numbers it failed to reach significance ($F_{(1,20)} = 0.45$, $p = 0.51$). The correlation for log reaction times was not significant ($r = 0.08$, $F_{(1,20)} = 0.14$, $p = 0.72$).

iii. Single-subject analysis

All subjects except two with developmental prosopagnosia had low accuracy scores on this short form of the Cambridge Face Memory Test. Only two subjects (L-IOT1, B-ATOT2) had poor accuracy on the short form of the Cambridge Bicycle Memory Test, though another was borderline (B-ATOT3). Ten of the 22 subjects–six with developmental and four with acquired prosopagnosia–met accuracy criteria for a putative classical dissociation, with a difference between bicycle and face test scores that exceeded the 95% prediction interval derived from the control group (Figure 2A).

Reaction times (Figure 2B) on the Cambridge Face Memory Test were increased in 6 of the 15 subjects with acquired prosopagnosia and in 8 of 12 subjects with the developmental form. On the Cambridge Bicycle Memory Test, in contrast to the mainly normal findings for accuracy, several prosopagnosic subjects had prolonged reaction times, including 5 of the 10 with acquired prosopagnosia who did the test and 2 of the 12 developmental subjects. Two subjects with developmental prosopagnosia met criteria for a putative classical dissociation in reaction times.

It is not clear how one should incorporate reaction time data into criteria for a putative classical dissociation that are based primarily on accuracy. We suggest that, at a minimum, to exclude confounding speed-accuracy trade-offs, as has been reported before in prosopagnosic studies (Gauthier et al., 1999), reaction times should be normal for the test with normal accuracy (i.e., bicycles). Eight prosopagnosic subjects meet these more restrictive criteria, for what we will call a "firm putative classical dissociation". While it is not necessary that reaction times be prolonged for the test with abnormal accuracy (i.e., faces), a putative classical dissociation in both accuracy and reaction times would make an even more definitive case for dissociation. This was seen in one subject, DP016.

The Bayesian standardized differences test allowing for covariates confirmed our results with minor differences, due to a slightly more liberal tendency to classify borderline results as significant. These results are reported in Table 7 following the recommended format of Table 2 in (Crawford, Garthwaite, & Porter, 2010). Thus R-AT3, DP021, and DP044 were now classified as having a borderline (p ranging from .0237 to .0358) putative dissociation in accuracy. Taking into account the reaction times, R-IOT4 would no longer meet our criteria for a firm putative classical dissociation, because of slightly prolonged reaction times on the Cambridge Bicycle Memory Test, while DP021 would. To follow a conservative definition, we classified results as showing dissociations only if both methods agreed.

One caveat deserves mention. One cannot be certain, particularly in subjects with acquired prosopagnosia, that prolonged reaction times alone (i.e., with normal accuracy) are proof of a subtle object processing problem on the Cambridge Bicycle Memory Test. Delayed processing could reflect non-specific effects of cerebral damage, such as (but not limited to) the visual field defects associated with occipitotemporal lesions. Studies with gaze-contingent techniques show that virtual hemianopia prolongs reading times and the time needed for shape processing (Bao, Rubino, Taylor, & Barton, 2015; Sheldon, Abegg, Sekunova, & Barton, 2012), for example. Currently there are no data on the impact of visual field defects on the Cambridge Face and Bicycle Memory Tests. However, one might reasonably expect that the effects of

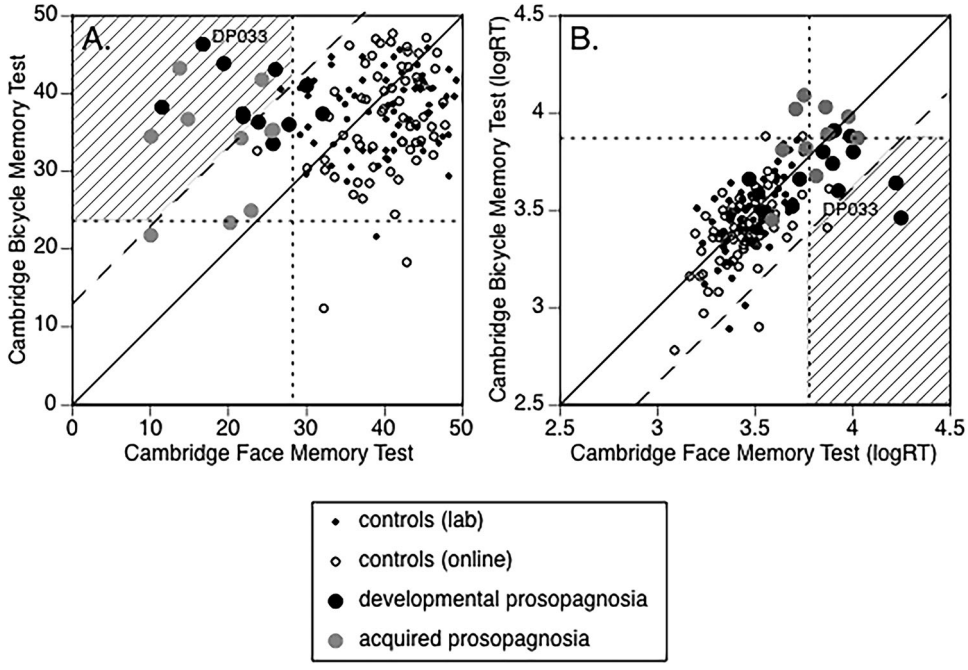

Figure 2. Age-adjusted results, Cambridge Bicycle and Face Memory Tests. A. Age-adjusted correct scores and B. age-adjusted log reaction time for the bicycle test are plotted against that of face test. Vertical and horizontal dotted lines show the 95% prediction limits for the individual tests, while the dashed oblique line indicates the 95% prediction limit for the difference between face and bicycle scores. Prosopagnosic subjects whose scores fall in the grey striped zones have a putative classical dissociation between face and bicycle scores. Data for DP033 are shown.

hemifield defects on both should be similar, given that the display layout and image sizes are similar between the two tests. One conservative position then may be that an object processing impairment is particularly suspect in those who have much longer reaction times for bicycle than face processing: e.g., L-lOT1, B-AT1, and R-AT1.

Experiment 3. Expert-adjusted car recognition (Barton et al., 2009)

Faces are a type of object for which it is assumed that almost all humans have considerable perceptual expertise. Face expertise may still show some variability, as in the other-race effect, which refers to the poorer recognition of faces from ethnic groups not frequently encountered by the subject (Anzures et al., 2013). This lies behind the rationale of assessing our North-American-raised subjects with tests that use Caucasian faces. For most other objects, though, expertise is highly variable across subjects, depending on both exposure and interest. This suggests that for a fair comparison between face and object processing, object expertise needs to be taken into account, which is point 11. This is the motivation behind reports of the recognition of prosopagnosic subjects for objects of their own particular expertise, such as a restaurant worker who could no longer recognize fruits and vegetables (de Renzi, Faglioni, Grossi, & Nichelli, 1991) or a racing fan who couldn't recognize horses (Newcombe, 1979) and the counter-examples of a soldier who could still recognize military insignia (Cole & Perez-Cruet, 1964), a car hobbyist who could still recognize a large number of cars (Sergent & Signoret, 1992), and a sheep farmer and a horse enthusiast who could identify animals they knew (McNeil & Warrington, 1993; Weiss, Mardo, & Avidan, 2016). While this approach can work with a single case, it is not feasible in a group study to administer tests that target the idiosyncratic expertise of each and every member of the group. With the realization that expertise is not a binary function but exists on a spectrum, we took the approach of using a single object category and gauging expertise by a verbal non-perceptual test of semantic knowledge about that category, and examining how visual recognition varied as a function of that index of expertise. This use of non-visual knowledge to index expertise in evaluating the results of

Table 7. Bayesian standardized differences test, experiment 2.

	Adjusted z-score		CFMT-CBMT	*p*-value	Estimated % of controls with greater greater discrepancy in the direction as the case		Effect size (Z-DCCC)	
	CFMT	CBMT	Difference	(2-tails)	Point	(95% CI)	Point	(95% CI)
ACCURACY								
Controls ($n = 139$)								
Mean	40.08	37.17						
s.d.	5.86	6.07						
Acquired prosopagnosia								
R-IOT1	−2.69*	−0.32	−2.38	0.0716	3.57	(0.89–8.72)	−1.87	(−2.37 to −1.36)
R-IOT3								
R-IOT4	−4.73*	−0.09	**−4.65**	**0.0007**	0.03	(0.00–0.19)	−3.66	(−4.40 to −2.89)
L-IOT1	−5.62*	−2.57*	**−3.06**	**0.0266**	1.34	(0.07–5.48)	−2.41	(−3.19 to −1.60)
B-IOT1								
B-IOT2	−5.62*	−0.46	**−5.16**	**0.0002**	0.01	(0.00–0.07)	−4.06	(−4.91 to −3.20)
B-ATOT1								
B-ATOT2	−3.71*	−2.29*	−1.42	0.2785	13.87	(5.82–25.13)	−1.12	(−1.57 to −0.67)
B-ATOT3	−3.21*	−2.03	−1.17	0.3699	18.40	(8.55–31.42)	−0.93	(−1.37 to −0.48)
R-AT1	−4.92*	1.01	**−5.93**	**0.0000**	0.00	(0.00–0.01)	−4.67	(−5.28 to −4.02)
R-AT2	−2.95*	0.76	**−3.72**	**0.0044**	0.22	(0.04–0.62)	−2.93	(−3.33 to −2.50)
R-AT3	−3.46*	−0.49	**−2.96**	**0.0237**	1.18	(0.28–2.99)	−2.34	(−2.77 to −1.88)
R-AT4								
B-AT1	−2.73*	−0.34	−2.39	0.0652	3.25	(1.32–6.23)	−1.88	(−2.22 to −1.54)
B-AT2								
Developmental prosopagnosia								
DP008	−3.42*	0.03	**−3.45**	**0.0112**	0.58	(0.03–2.38)	−2.72	(−3.41 to −1.98)
DP014	−3.87*	1.11	**−4.97**	**0.0002**	0.01	(0.00–0.05)	−3.92	(−4.48 to −3.31)
DP016	−2.64*	0.98	**−3.62**	**0.0066**	0.33	(0.03–1.22)	−2.85	(−3.41 to −2.25)
DP021	−2.81*	−0.08	**−2.73**	**0.0356**	1.79	(0.62–3.77)	−2.15	(−2.50 to −1.78)
DP024	−1.50	0.03	−1.53	0.2332	11.73	(6.98–17.72)	−1.21	(−1.48 to −0.93)
DP033	−4.37*	1.51	**−5.88**	**0.0000**	0.001	(0.00–0.005)	−4.64	(−5.32 to −3.90)
DP035	−3.41*	−0.03	**−3.37**	**0.0103**	0.52	(0.09–1.50)	−2.66	(−3.12 to −2.17)
DP038	−1.88	0.64	−2.52	0.0503	2.55	(1.14–4.66)	−1.99	(−2.28 to −1.68)
DP039	−5.35*	0.17	**−5.52**	**0.0001**	0.003	(0.00–0.02)	−4.35	(−5.08 to −3.59)
DP044	−3.04*	−0.15	**−2.89**	**0.0266**	1.34	(0.37–3.15)	−2.28	(−2.67 to −1.86)
DP201	−2.27*	−0.19	−2.08	0.1158	5.54	(1.42–13.20)	−1.64	(−2.19 to −1.12)
DP202	−2.69*	−0.60	−2.08	0.1084	5.40	(2.32–9.94)	−1.64	(−1.99 to −1.28)
LOG RESPONSE TIME								
Controls ($n = 139$)								
Mean	3.46	3.44						
s.d.	0.14	0.19						
Acquired prosopagnosia								
R-IOT1	2.89*	2.40*	0.49	0.6076	30.38	(13.43–51.44)	0.54	(−0.04–1.11)
R-IOT3								
R-IOT4	3.99*	2.26*	1.73	0.0798	3.99	(0.44–12.88)	1.89	(1.13–2.62)
L-IOT1	2.82*	3.13*	−0.31	0.7517	37.58	(15.35–63.62)	−0.34	(−1.02–0.35)
B-IOT1								
B-IOT2	3.65*	2.86*	0.79	0.4276	21.38	(5.27–46.60)	0.86	(0.08–1.62)
B-ATOT1								
B-ATOT2	2.47*	1.26	1.21	0.1968	9.84	(4.60–17.16)	1.32	(0.95–1.68)
B-ATOT3	1.25	1.95	−0.70	0.4549	22.74	(12.97–34.61)	−0.77	(−1.13 to -0.40)
R-AT1	1.72	3.09*	−1.37	0.1469	7.35	(2.71 tp 14.55)	−1.50	(−1.92 to −1.06)
R-AT2	2.11	1.99	0.11	0.9040	45.20	(31.79–59.07)	0.12	(−0.23–0.47)
R-AT3	0.88	0.05	0.82	0.3763	18.82	(12.23–26.63)	0.90	(0.62–1.16)
R-AT5								
B-AT1	2.04	3.46*	−1.43	0.1337	6.68	(2.13–14.22)	−1.56	(−2.03 to −1.07)
B-AT2								
Developmental prosopagnosia								
DP008	3.08*	1.57	1.50	0.1269	6.35	(0.94–18.22)	1.64	(0.91–2.35)
DP014	3.82*	1.89	**1.94**	**0.0442**	2.21	(0.37–6.38)	2.12	(1.52–2.68)
DP016	5.39*	1.06	**4.33**	**0.0002**	0.001	(0.00–0.01)	4.73	(3.84–5.57)
DP021	5.57*	0.12	**5.45**	**0.0000**	0.00	(0.00–0.00)	5.95	(5.07–6.75)
DP024	3.12*	2.47*	0.65	0.4926	24.63	(11.84–40.83)	0.71	(0.23–1.18)
DP033	3.29*	0.84	**2.44**	**0.0114**	0.57	(0.06–2.01)	2.67	(2.05–3.25)
DP035	1.61	0.42	1.19	0.2049	18.25	(5.05–17.39)	1.30	(0.94–1.64)
DP038	0.59	0.30	0.29	0.7586	37.93	(31.16–44.97)	0.31	(0.13–0.49)
DP039	1.87	1.20	0.68	0.4758	23.79	(11.00–40.34)	0.74	(0.24–1.23)
DP044	3.73*	2.35*	1.38	0.1501	7.50	(2.11–16.85)	1.50	(0.96–2.03)
DP201	2.72*	1.91	0.81	0.4005	20.02	(7.03–38.79)	0.89	(0.28–1.47)
DP202	0.03	1.20	−1.16	0.2126	10.63	(6.31–16.11)	−1.27	(−1.53 to −0.99)

CFMT = Cambridge Face Memory Test, CBMT = Cambridge Bicycle Memory Test.
Asterisk = abnormal adjusted CFMT, CBMT scores.
Bold type = significant dissociation between faces and bicycles.
Underline = different from analysis reported in Figure 2 and Table 10.
Shaded–meeting criteria for firm putative classical dissociation.

perceptual testing is an approach that others are also developing (Van Gulick, McGugin, & Gauthier, 2015).

A critical assumption of this approach is that prosopagnosia, being a disorder of visual recognition, would not be associated with verbal semantic deficits, unlike the case with multimodal disorder of person recognition (Barton & Corrow, 2016b; Blank, Wieland, & von Kriegstein, 2014). Our prosopagnosic subjects were evaluated for familiarity and occupational sorting of famous names (Barton et al., 2001) to exclude a verbal semantic deficit for people, and normal performance on this would also make a general semantic deficit unlikely. Nevertheless, if there were deficits for object knowledge, we would anticipate that this would reduce both perceptual and verbal scores and bias against the finding of an expertise-adjusted deficit in object recognition.

We used the category of cars. While it is unlikely that humans would have another object type with a "perceptual space" as densely populated with exemplars as faces, our survey found 457 car models available in North America over a 55-year period, many with several model iterations. Hence a highly expert car enthusiast has a potential model space population of several thousands. This may permit some comparison with faces, as some estimate that humans can remember up to 4,000 faces (Jenkins, 2017), thus addressing point 10 to a degree. (While words may be even better, with vocabulary estimates of 20,000–35,000, words may have a special status in relation to faces, as reflected in the many-to-many hypothesis (Behrmann & Plaut, 2013; Hills et al., 2015; Plaut & Behrmann, 2011).) Because this is a test of long-term recognition, the issue in point 8 of using different images between learning and test phases does not apply. Furthermore, faces and cars are objects for which humans tend to report the most expertise (McGugin, Richler, Herzmann, Speegle, & Gauthier, 2012). While recognition performance is minimally correlated between cars and faces in healthy subjects (McGugin et al., 2012), there is some evidence to suggest that both cars and faces involve processing that is distinct from the general object mechanisms operating with novel objects or other object types (Cepulic, Wilhelm, Sommer, & Hildebrandt, 2018; Richler, Wilmer, & Gauthier, 2017). These features make expertise-adjusted assessment of car recognition of particular interest in prosopagnosia.

Methods

Subjects

All 12 subjects with developmental prosopagnosia participated. Two of the 15 subjects with acquired prosopagnosia did not (B-ATOT1, B-lOT1), as they had been evaluated before the creation of this test. Forty healthy subjects served as controls, 10 female, with mean age of 31.0 years (s.d. 14.3, range 18–65); 33 of these controls had participated in our initial study (Barton et al., 2009).

Self-assessment of knowledge of cars

Subjects rated their car expertise on 18 Likert scales, ranging from 0 (novice) to 10 (expert), with one scale for each of six decades (1950s–2000s), for three different regions of the manufacturers (North American, Asian and European). The average of these 18 scores was their self-rating of car knowledge.

Assessment of verbal semantic knowledge of cars

This was a list of 457 commercial car models available in North America between 1950 and 2005, excluding trucks and sport-utility vehicles. These were divided into 3 sub-lists, one for models whose designation was a name (e.g., Esprit), one for models whose designation was a character string beginning with a letter (e.g., F430), and one for models whose designation was a character string beginning with a number (e.g., 911). Subjects were given these 3 lists in random order and asked to write the name of the manufacturer of each model. They were given a list of the possible answers, which comprised 63 manufacturers (20 North American, 16 Asian, 27 European). They were encouraged to guess and told that there would be no penalty for incorrect answers. To adjust approximately for the probability of exposure, we weighted correct answers for the number of years a model was available, by giving 0.1 points for each year. The sum of these weighted correct scores was our "verbal semantic score".

Assessment of visual semantic knowledge of cars

We selected 150 of the 457 models, distributed approximately evenly over the 6 different decades and the 3 different continents of manufacture, with examples of all car configurations, such as sedans, sport cars, and station wagons, and from a variety of viewpoints. We obtained full-colour images of these

cars in naturalistic settings from the internet. We used Adobe Photoshop CS2 9.0.2 (www.adobe.com) to eliminate lettering or badges that identified the model or manufacturer. We created a random ordering of images, with the same order used for all subjects. We displayed images on a computer monitor in standard dim lighting, with Superlab Pro 2.0.4 (www.cedrus.com). Subjects were allowed to look at each image as long as they wished. Each image was numbered and subjects were asked to write on paper the model, manufacturer and decade of manufacture of the car shown. Subjects were encouraged to guess, but could leave blank any item for which they had no guess and were not penalized for incorrect answers. Short breaks were allowed.

Three separate scores were calculated, one for each of the three answers requested (model, manufacturer and decade). These scores were not weighted by years of availability, since each image is of a specific car made in a specific year, and not necessarily representative of all permutations of that model over the different years of manufacture. Finally, we calculated a "weighted visual score" as in our prior work (Barton et al., 2009), by multiplying the manufacturer score by 1, the model score by 1.6, and the decade score by 0.02 and summing the three resulting values. These weightings had generated the optimum correlation between verbal semantic and weighted visual scores in the initial group of 33 healthy controls.

Statistical analysis

Consistent with our prior report for a subset of our controls (Barton et al., 2009), there was a significant correlation ($r = 0.64$) between self-knowledge and the verbal semantic knowledge score. Compared to the verbal semantic score, the self-knowledge index was less correlated with visual recognition for decade ($r = 0.36$ versus 0.50), make ($r = 0.65$ versus 0.90), and model ($r = 0.67$ versus 0.92). Therefore we focused our analysis on the relationship between the verbal semantic knowledge and visual car recognition.

First, to compare the relationship between verbal semantic and weighted visual scores in prosopagnosic patients to that of the healthy subjects, we used a pairwise covariance analysis (http://department.obg.cuhk.edu.hk/ResearchSupport/Compare_2_regressions.asp) to determine if the regression slopes and slope-adjusted means differed between any two of the three groups.

Second, we were interested in the role of car expertise (as indexed by the verbal semantic score) in predicting the ability of subjects to recognize each of the three items of decade of make, manufacturer, and model. These are listed in increasing order of specification, and we predicted that the more specific the item, the greater the influence of expertise. To compare the strength of the correlations for each of these three responses with the verbal semantic score, we used a method to compare two overlapping correlations based on dependent groups, using Pearson and Filon's z method for determining significance (Diedenhofen & Musch, 2015).

Third, to classify visual recognition scores at an individual level, we considered this as equivalent to asking if the perceptual score of a prosopagnosic subject was dissociated from their semantic score in one direction (i.e., lower than expected). We corrected for effects of age by using the Bayesian standardized differences test allowing for covariates, with the BSDT_Cov_Raw.exe programme used in Experiment 2, reporting effect sizes and one-tailed *p*-values for the difference between perceptual and semantic results. This essentially reported an age-corrected expertise-adjusted assessment of their visual car recognition.

Item-specific concordance analysis

This was aimed at probing for residual expertise effects at a group level in the prosopagnosic cohorts. We took from the verbal semantic test the 150 items that had a corresponding car image in the visual recognition test and noted for each item the answers given by the subjects on both the verbal and visual tests. We then calculated on a group level the odds of identifying a car visually if the subject had been able to provide correct verbal information about that car, and the odds of correct visual identification if they had not been able to do so verbally. This was done separately for the answers regarding model, manufacturer and decade. The results were analyzed with the Mantel-Haenszel method (Fleiss, 1981). First, this determined whether overall the odds differed between items with and without correct item-specific verbal semantic knowledge (i.e., was the overall odds ratio greater than 1). Second, it determined whether the odds ratios were homogenous across the three groups (control, acquired and developmental prosopagnosia).

Our prior study had shown that, in healthy subjects, the chief effect of car expertise as reflected in

the verbal semantic score was to reduce the odds ratio for visual recognition of the model (Barton et al., 2009). That is, for less expert subjects the odds of naming the model of the car they saw (e.g., Mustang) was substantially lower if they did not show verbal semantic knowledge about that car (e.g., knowing that a Mustang was made by Ford), whereas this effect was reduced in more expert subjects. We asked whether prosopagnosia would reduce the difference between less and more expert subjects. We chose an arbitrary verbal semantic score of 100 to divide both the control and prosopagnosic subjects into less and more expert groups. Given that the initial analyses did no show much difference between developmental and acquired prosopagnosia, we combined these two groups together. We then used the Mantel-Haenszel method to test whether the odds ratios for the more-expert group differed from those for the less-expert group (Fleiss, 1981).

Results

1. The relationship between verbal semantic and weighted visual scores

i. Group analysis. As in our prior report (Barton et al., 2009), the weighted visual score was strongly correlated with the verbal semantic score in controls ($r = 0.94$) (Figure 3). There was no significant difference in the slope ($t_{(36)} = 1.12$, $p = 0.27$) or the slope-adjusted means ($t_{(37)} = 0.28$, $p = 0.38$) between male and female control subjects, indicating that any gender differences reflect mainly expertise differences.

The weighted visual score was also strongly correlated with the verbal semantic score in both our acquired ($r = 0.82$) and developmental ($r = 0.83$) prosopagnosic groups. However, the slopes of the regression lines for the acquired ($b = 0.24$) and developmental ($b = 0.33$) prosopagnosic groups were only about half that for the controls ($b = 0.61$). The covariance analysis confirmed, first, significant differences between the slope of the regression for control subjects and those for either the acquired ($t_{(49)} = 5.51$, $p < 0.0001$) or developmental ($t_{(49)} = 2.67$, $p = 0.010$) cohorts, but the slopes did not differ between the two prosopagnosic groups ($t_{(22)} = 0.97$, $p = 0.34$). Second, the slope-adjusted mean visual recognition score of control subjects was greater than those of either the acquired ($t_{(50)} = 5.53$, $p < 0.0001$) or developmental ($t_{(50)} = 3.21$, $p = 0.002$) prosopagnosic subjects, but again did not differ between the two prosopagnosic groups ($t_{(23)} = 1.29$, $p = 0.21$).

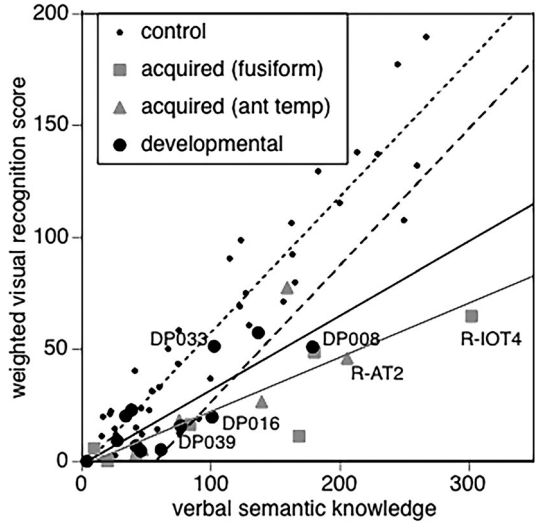

Figure 3. Results, weighted visual score, Expertise-adjusted car recognition test. A weighted composite score that combines all three answers (0.02*decade + 1.0*manufacturer + 1.6*model) is plotted as a function of verbal semantic knowledge. The linear regressions of visual recognition against verbal semantic knowledge are shown for controls (dotted line), acquired prosopagnosia (grey line), and developmental prosopagnosia (black line). Individual subjects with abnormal scores are those falling below the dashed line, which indicates the lower 95% prediction limit. For acquired prosopagnosia, different symbols are used for those with lesions involving at least the right fusiform gyrus, and those with lesions limited to the anterior temporal lobes (ant temp). We indicate the results for DP033 and DP039, the best candidates for intact object recognition across all three tests, and DP016, DP008, R-AT2, and R-IOT4, who have impaired expertise-adjusted car recognition despite good performance on our two other object tests.

This analysis thus showed four things. First, on average the prosopagnosic groups recognized fewer cars than predicted by the relationship between the verbal semantic and weighted visual scores in healthy controls. Second, the slope analysis revealed that for every increment in car expertise as indexed by the verbal semantic score, the prosopagnosic subjects had only about half the gains in visual car recognition that were shown by healthy controls. Third, this impairment was similar in both acquired and developmental prosopagnosia.

The fourth point relates to the question of whether car expertise effects are still evident in our prosopagnosic group. Even though the two prosopagnosic cohorts showed poorer car recognition than predicted by their verbal semantic knowledge about cars, there

was still a strong correlation between visual car recognition and verbal semantic knowledge, in both acquired ($r = 0.82$, $F_{(1,12)} = 24.3$, $p < 0.0003$) and developmental ($r = 0.84$, $F_{(1,11)} = 25.5$, $p < 0.0003$) prosopagnosic groups. Hence expertise still played a strong role in determining visual car recognition in prosopagnosic subjects. The presence of residual expertise was explored by three further analyses below.

ii. Single-subject analysis. A limitation of this test is that those with a verbal semantic score of less than 56.6 cannot be classified at a single-subject level since the lower 95% prediction limit is zero or less in this range. This excluded 11 of the 25 subjects from consideration. Of the remaining 14, five of the eight subjects with acquired prosopagnosia could be classified as having impaired visual car recognition (Figure 3). These included three of the four subjects with lesions that included the fusiform gyrus (R-IOT3, R-IOT4, and B-IOT2) and two of the four subjects with lesions limited to anterior temporal cortex (R-AT2 and R-AT5). Among the developmental prosopagnosic group, two of six subjects had impaired car recognition (DP008 and DP016). If we limit consideration to those we classified as experts by the arbitrary criterion of a verbal semantic knowledge score of more than 100, then five of six subjects with acquired prosopagnosia and two of four with developmental prosopagnosia were impaired.

2. Expertise effects

i. The relationship between a subject's car expertise (verbal semantic score) and the degree of expertise demanded in visual recognition. In our control subjects, all three types of responses for visual recognition were correlated with the verbal semantic score (all $p < 0.001$). However, Figure 4 shows that the verbal semantic score is more strongly correlated with the ability to visually recognize the manufacturer ($r = 0.90$) or model ($r = 0.92$) of a car than with the ability to name the decade when it was made ($r = 0.50$). Comparisons showed that correlation coefficients for naming the decade of make was lower than those for recognizing either the manufacturer ($z = 3.61$, $p = 0.0003$) or the model ($z = 3.56$, $p = 0.0004$), but those for the latter two did not differ significantly ($z = 0.54$, $p = 0.58$). Thus, an individual's car expertise was a stronger predictor of their ability to recognize a car visually at a more specific level (manufacturer or model) than at a more general level (decade).

Would our prosopagnosic subjects show a similar interaction between subject expertise and the specificity of recognition demanded? Figure 4 also shows that this is the case. Given that the two groups had similar results in our first analysis, we combined the two prosopagnosic groups to improve the power and stability of the correlations again (Schonbrodt & Perugini, 2013). The correlation comparisons showed a similar pattern to that seen in controls: the

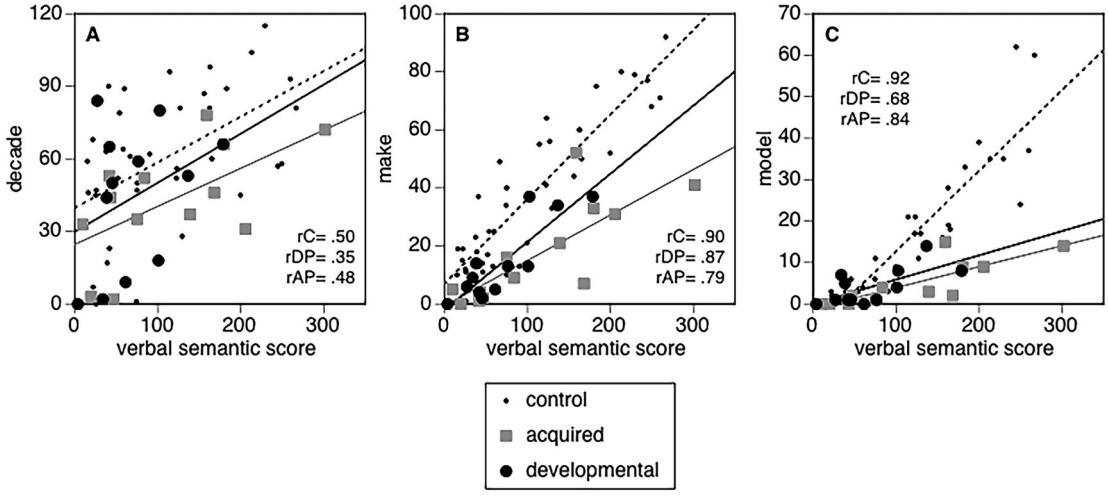

Figure 4. Results, Expertise-adjusted car recognition test. In all three graphs a visual recognition score is plotted as a function of each subjects' verbal semantic knowledge score. The vertical axis plots the number of correct scores for decade of make (A), the manufacturer (B), and the model (C). Lines indicate the linear regressions of visual recognition scores against verbal semantic knowledge, for controls (dotted line), acquired prosopagnosia (grey line), and developmental prosopagnosia (black line). Correlation coefficients are given.

correlation with the verbal semantic score was lower for recognizing a car's decade ($r = 0.40$) than its manufacturer ($r = 0.79$, $z = 2.55$, $p = 0.011$) or model ($r = 0.76$, $z = 2.08$, $p = 0.038$), while the correlations did not differ significantly between the latter two ($z = 0.62$, $p = 0.54$).

ii. Item concordance of verbal semantic knowledge with visual recognition. For the control subjects, the odds of visually recognizing an individual car at any level (model, manufacturer, decade) were greater if they had answered correctly for that car on the verbal semantic test. This effect increased as the level of visual recognition became more specific: the odds ratio was 2.08 (s.e. 0.13) for decade, 5.50 (s.e. 0.36) for manufacturer, and 20.62 (s.e. 2.45) for model ($\chi_{homog} = 241$, $p < 0.0001$). In other words, subjects who knew that Mustangs were made by Ford were only twice as likely to provide the correct decade of a pictured Mustang, but twenty times as likely to identify it as a Mustang, compared to subjects who did not know that information. Thus verbal semantic knowledge about an individual item became a better predictor of visual recognition when the level of recognition demanded was more specific.

One could speculate that one effect of loss of expert visual car recognition would be a degradation of this effect of recognition specificity. However, prosopagnosic subjects showed the same pattern as controls, with increasing odds ratios as the visual recognition became more specific, from decade to manufacturer to model (Figure 5, Table 8). This was true for both developmental ($\chi_{homog} = 27.2$, $p <$

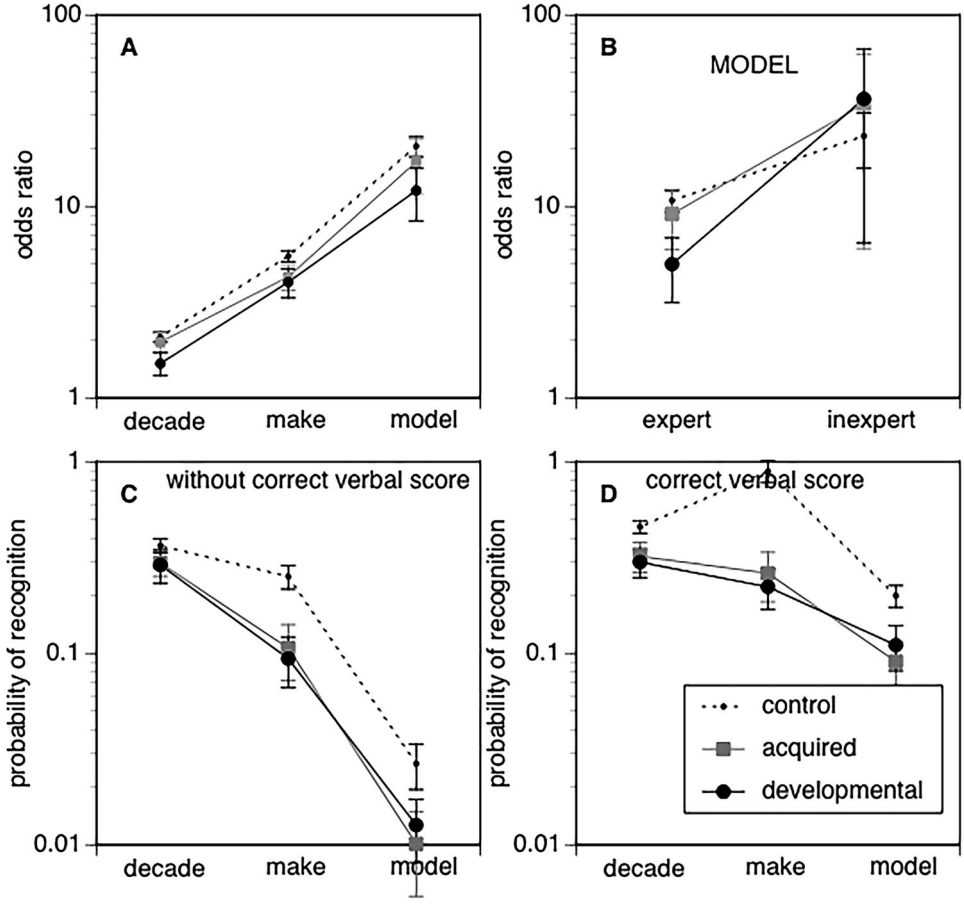

Figure 5. Effects of expertise in the Expertise-adjusted Car Recognition Test. A shows the odds ratio of visual recognition related to verbal semantic knowledge, for model, manufacturer, and decade. All three subject groups show a similar effect, with greater odds ratio for the more demanding task of identifying the model of the car. B shows the effects of subject expertise on the odds ratio of visually recognizing the model of the car: less expert subjects show greater odds ratio than more expert subjects, and this is true of all three groups. C and D show that the reason for the similar effect on odds ratio in A is due to reduced probability of recognition by the prosopagnosic groups independent of whether they did (D) or did not (C) possess correct verbal semantic knowledge about the specific car.

Table 8. Odds ratios for car recognition.

Group	Odds ratio, Decade (se)		Odds ratio, Manufacturer (se)		Odds ratio, Model (se)		*X*	*p*
Control	2.08	0.13	5.50	0.36	20.62	2.45	241.77	<0.0001
Developmental	1.51	0.21	4.02	0.70	12.10	3.71	27.24	<0.0001
Acquired	1.96	0.23	4.29	0.65	17.09	5.45	26.41	<0.0001
X	4.21		4.50		1.77			
p	0.12		0.11		0.41			

0.0001) and acquired ($\chi_{homog} = 26.4$, $p < 0.0001$) cohorts. Indeed, contrasts across the three subject groups showed no difference in the odds ratios for manufacturer, model or decade.

The reason for the similarity in the odds ratios across the three subject groups is apparent when we look separately at the probability of recognition for cars with correct answers and that for cars with incorrect answers on the verbal semantic test – i.e., the numerator and denominator of the odds ratio (Figure 5, C and D). Prosopagnosic subjects had a lower likelihood of visual recognition regardless of whether they knew the manufacturer of the model.

iii. Item concordance and the influence of subject expertise. Finally, our prior study of item concordance in healthy subjects showed that for the most specific form of visual recognition, i.e., the model of the car, more expert subjects showed a smaller effect of verbal semantic knowledge than did less expert subjects (Barton et al., 2009). This was because less expert subjects seldom recognized the model of a car visually when they did not know which manufacturer made that model. The larger prosopagnosic cohorts in the current study allowed us to examine this effect of subject expertise on concordance effects in this disorder.

We arbitrarily divided the groups into less and more expert subjects using a criterion of 100 on the test of verbal semantic knowledge. Again, we pooled the developmental and acquired prosopagnosic subjects, given the small numbers involved. The distribution of expertise scores did not differ between the controls and the prosopagnosic cohorts in both the less expert ($t_{(35)} = 0.37$, $p = 0.71$) and the more expert groups ($t_{(26)} = 0.50$, $p = 0.62$) (Table 9).

We began by reviewing the effects of subject expertise in the control group. First, as a general observation, for all three questions of decade, make and model, both less and more expert subjects were more likely to give the right answer on a visual recognition test if they had also given the right answer for that test item on the verbal semantic test. This is shown by the fact that the confidence intervals for all odds ratios did not include the value of 1 (Table 9). Second, the odds ratios were least for decade of make and greatest for model name; the test for homogeneity of odds ratios showed a significant difference across model, manufacturer, and decade for both less-expert ($\chi^2_{homog} = 58.6$, $p < 0.0001$) and more-expert subjects alike ($\chi^2_{homog} = 133.1$, $p < 0.0001$). Thus, as the information demanded in the visual recognition task became more specific, the dependence of the probability of visual recognition on the accuracy of verbal semantic knowledge also increased.

The third and key observation is that the test for homogeneity of odds ratios showed that the less and more expert control groups differed only in odds ratios for visual recognition of the model ($\chi^2_{homog} = 5.00$, $p < 0.03$), but not for recognition of manufacturer or decade of make. Less expert control

Table 9. Concordance effects in less and more car-expert subjects.

CONTROL SUBJECTS				
	Less expert ($n = 22$)		More expert ($n = 18$)	
	Expertise score		Expertise score	
	Mean	s.d.	Mean	s.d.
	45.9	21.5	178.2	54.7
	odds ratio	(CI)	odds ratio	(CI)
Year	1.34	(1.1,1.7)	1.71	(1.5, 2.0)
Make	3.47	(2.7, 4.4)	3.90	(3.3, 4.6)
Model*	23.30	(14.9, 36.6)	10.72	(8.6, 13.4)
PROSOPAGNOSIA				
	Less expert ($n = 15$)		More expert ($n = 10$)	
	Expertise score		Expertise score	
	Mean	s.d.	Mean	s.d.
	43.10	23.5	167.20	58.0
	odds ratio	(CI)	odds ratio	(CI)
Year	1.12	(0.8, 1.7)	1.50	(1.2, 1.9)
Make*	4.34	(2.7, 7.0)	2.31	(1.8, 3.0)
Model*	28.64	(15.5, 53.1)	6.99	(4.5, 10.9)

*Significant difference between less and more expert subjects.
CI = 95% confidence interval of odds ratio.

subjects rarely recognized the model of car for which they had not been able to provide the correct verbal semantic information, and thus were 23.3 times more likely to name the model of a visually presented car if they had been able to match the model name with its manufacturer, compared to an odds ratio of 10.8 for more expert subjects.

The effect of subject expertise in the pooled prosopagnosia group was similar if not greater (Table 9, Figure 5). Less expert prosopagnosic subjects were 28.6 times more likely to identify the model of a seen car if they had matched the model name to its manufacturer, whereas more expert subjects were only 7 times more likely to do so ($\chi^2_{homog} = 7.34$, $p < 0.007$). Indeed, there was even a similar effect of subject expertise for identifying the manufacturer of a seen car: less expert prosopagnosic subjects were 4.3 times more likely to do so if they could match the name of the model to the name of the manufacturer, but more expert subjects only 2.3 times more likely ($\chi^2_{homog} = 4.77$, $p < 0.03$).

Single-subject comparisons across experiments

Accuracy scores alone on the Cambridge Bicycle Memory Test were relatively insensitive to object processing deficits, since 20 of 22 subjects scored in the normal range despite the abnormalities many showed on the two other tests (Table 10). With more rigorous criteria, a putative classical dissociation[2] was seen in ten, seven of whom also had normal reaction times. Among these seven, four performed normally on all Old/New Tests and three fell in the grey zone, not meeting stringent criteria for normal or abnormal performance.

While this suggests reasonable agreement between the Old/New Tests and the Cambridge Bicycle Memory

Table 10. Single-subject comparison across the three tests.

	Experient 1				Experiment 2				Experiment 3			
	Old/new				Bicycle memory test				Car expertise			
	Number	Number abnormal			Accuracy /48		Reaction time		Verbal	Weighted	Age-adjusted	
Subject	of tests	A′	RT	Classification	CFMT	CBMT	CFMT	CBMT	semantic	visual	Effect size	*p* value
Means					40.1	37.2	3073	2993				
Acquired prosopagnosia												
R-IOT1	2	0	0	?	31*	37	6397*	7889*	83.6	16.44	−1.52	0.080
R-IOT3	2	2	0	abnormal*	28*	–	8289*	–	179.9	48.72*	−2.89	0.008
R-IOT4	3	0	1	grey	**22***	**39**	8657*	7434#	301.8	64.84*	−6.71	<0.0001
L-IOT1	4	3	1	abnormal*	17*	24*	5964*	10912*	*42.9*	*4.88*	*−0.55*	*0.306*
B-IOT1	4	1	1	grey	29*	–	4460	–	–	–		
B-IOT2	4	2	1	abnormal*	**18***	**37**	7595*	9694*	168.1	11.12*	−4.83	<0.0001
B-ATOT1	2	2	0	abnormal*	21*	–	4439	–	–	–		
B-ATOT2	2	2	0	abnormal*	19*	23*	6706	4728	*9.5*	*5.66*	*0.16*	*0.440*
B-ATOT3	0	–	–	–	20*	24	4726	6419	*19.6*	*0.06*	*−0.68*	*0.269*
R-AT1	4	0	0	normal	**13***	**43**	5191	10537*	*46.6*	*5.24*	*−1.23*	*0.127*
R-AT2	4	0	0	normal	**25***	**42**	5644	6561	205.5	46.02*	−4.68	<0.0001
R-AT3	4	1	0	grey	24*	35	3612	2808	159	77.56	−0.92	0.193
R-AT5	2	1	0	grey	27*	–	9249*	–	139.2	26.54*	−2.80	0.008
B-AT1	2	1	0	grey	25*	35	5707	12406*	71.5	17.32	−1.43	0.091
B-AT2	4	0	0	normal	25*	–	2515	–	*41.7*	*3.66*	*−0.74*	*0.246*
Developmental prosopagnosia												
DP008	4	0	0	normal	**30***	**40**	6268*	5517	178.7	51.12*	−2.82	0.008
DP014	4	0	2	grey	**23***	**45**	9069*	6284	61.2	5.18	−1.47	0.086
DP016	4	0	0	normal	**32***	**45**	**14077***	**4389**	100.8	19.76*	−1.92	0.040
DP021	1	0	0	?	26*	37	**17213***	**2893**	*33.8*	*20.24*	*0.28*	*0.397*
DP024	4	0	0	normal	34	38	7633*	8093*	*45.4*	*4.6*	*−1.03*	*0.167*
DP033	4	0	0	normal	**22***	**48**	7270*	3991	102.4	51.4	−0.14	0.448
DP035	4	3	0	abnormal*	**25***	**38**	4483	3301	*41.8*	*6.9*	*−0.67*	*0.265*
DP038	4	0	0	normal	30	41	3525	3120	*27.1*	*9.28*	*−0.20*	*0.426*
DP039	4	0	0	normal	**17***	**40**	4571	4654	76.4	15.78	−1.27	0.125
DP044	4	0	0	normal	26*	37	9157*	7681*	136.5	57.46	−1.29	0.112
DP201	4	0	0	normal	34*	38	5910*	6390	*38.3*	*22.88*	*0.64*	*0.276*
DP202	4	0	0	normal	24*	33	3083	4604	*3.7*	*0*	*0.01*	*0.497*

CFMT–Cambride Face Memory Test, CBMT–Cambridge Bicycle Memory Test.
? Not enough testing, – not done, * abnormal score.
not a firm dissociation by Bayesian standardized differences test.
"Grey" - not meeting criteria for normality or impairment.
Bold type–putative classical dissociation for bicycle test.
Italic type–insufficient car expertise for single-subject classification.
Shaded–definitively normal (exp 1 or 3) or meeting criteria for firm putative classical dissociation (exp 2).

Test when strict criteria are applied for both, there were discrepancies. One subject (DP035) showed a putative classical dissociation for bicycles despite abnormal discrimination on three of four Old/New Tests. In the other direction, while lack of a putative classical dissociation cannot be taken as a discrepancy in the 10 subjects with normal performance on all Old/New Tests, three of these subjects (R-AT1, DP024, DP044) had prolonged reaction times on the Cambridge Bicycle Memory Test.

What does consideration of expertise buy us? Again, we can only comment on expertise-adjusted car recognition in the 14 subjects with a verbal semantic score above 56.6. Of the four subjects with less car-expertise (i.e., verbal semantic score between 56.6 and 100), none were abnormal on expertise-adjusted car recognition, and none were abnormal on the Old/New Tests. Two (DP014, DP039) showed a firm putative classical dissociation on the Cambridge Bicycle Memory Test. Two (B-AT1, R-IOT1) had prolonged reaction times on the latter test, but given the reservations about reaction times in patients with cerebral damage, it is not certain that this represents a discrepancy.

The results are more telling in the ten subjects with greater car expertise (i.e., verbal semantic score greater than 100). Two of these subjects were impaired on the Old/New Tests (R-IOT3, B-IOT2) and both were also impaired on expertise-adjusted car recognition. Three scored in the grey zone on the Old/New Tests, and two of these were impaired on expertise-adjusted car recognition, despite the fact that one (R-IOT4) showed a putative classical dissociation on the Cambridge Bicycle Memory Test. Five were normal on all Old/New Tests, four of whom also showed a firm putative classical dissociation; nevertheless, three of these five (R-AT2, DP008, DP016) were impaired on expertise-adjusted car recognition. These observations suggest that expertise-adjusted car recognition may be more sensitive to object processing deficits than the other tests, especially among car experts.

If we take all the results together, is there strong evidence for intact object recognition in any one subject? The best evidence was found in DP033, who was normal on all eight old/new indices, showed a putative classical dissociation and normal reaction times on the Cambridge Bicycle Memory Test, and had normal expertise-adjusted car recognition with a verbal semantic score in the more expert range. DP039 had a similar pattern of results, but his borderline low result on expertise-adjusted car recognition, along with a verbal semantic score in the less expert range, makes this result less convincing. Among the acquired prosopagnosic cohort, R-AT3 came the closest, with an expert verbal semantic score and normal expertise-adjusted car recognition, only one low A' score on the four Old/New Tests, and normal accuracy and reaction times on the Cambridge Bicycle Memory Test, though without meeting criteria for a putative classical dissociation.

What of the 11 whose verbal semantic score for cars was too low to permit classification of their visual car recognition scores? Six had normal performance on all four Old/New Tests, but none of these had a firm putative classical dissociation on the Cambridge Bicycle Memory Test. R-AT1 came closest, with a putative classical dissociation between faces and bicycles but very prolonged reaction times for the latter. Thus, even if these had been tested on a category for which they were more expert than cars, none would have achieved the pattern of normal object performance across tests that was seen in DP033 or DP039.

Discussion

To summarize, at the group level the acquired prosopagnosic cohort was impaired on the Old/New Tests, slower but accurate on the Cambridge Bicycle Memory Test, and had reduced expertise-adjusted car recognition. The developmental prosopagnosic cohort performed similar to controls on the Old/New Tests, were slower but accurate on the Cambridge Bicycle Memory Test, but had reduced expertise-adjusted car recognition. The single-subject analyses showed considerable heterogeneity. In acquired prosopagnosia, impairments on the Old/New Tests were limited to those with occipitotemporal lesions, while subjects with either occipitotemporal or anterior temporal lesions could be impaired on expertise-adjusted car recognition. In developmental prosopagnosia, only one subject was consistently abnormal on the Old/New Tests, none had poor accuracy on the Cambridge Bicycle Memory Test though two had prolonged reaction times, and two of six had reduced expertise-adjusted car recognition. Considering both groups,

putative classical dissociations between face and bicycle processing were found in ten of 20 subjects, seven of whom also had normal reaction times for bicycles, yet half of these ten had abnormal expertise-adjusted car recognition. Overall, two developmental prosopagnosic subjects performed normally on all indices of all three experiments, with the most definitive evidence of intact object recognition belonging to one who was classified as a car expert by our criteria.

Both the single-subject and group data suggest that the expertise-adjusted test of car recognition may be more sensitive to object processing deficits in prosopagnosia, with both developmental and acquired prosopagnosic cohorts recognizing about half as many cars as they should for their degree of expertise. This was particularly true in subjects with greater expertise with cars. While this would be consistent with impairment at an expert level of object processing, we nevertheless found evidence of residual expertise effects in the cohorts' recognition performance. Thus they show reduced rather than absent expert car recognition.

Overall, the results support the prior impression of heterogeneity. If the bar was set high for proof of intact object recognition, we found one, possibly two subjects with developmental prosopagnosia who met such criteria, namely normal discrimination and reaction times on all Old/New Tests, a putative classical dissociation with normal reaction times on the Cambridge Bicycle Memory Test, and normal expertise-adjusted car recognition. On the other hand, of the 10 subjects whose verbal semantic scores indicated that they were relatively expert with cars, seven had poorer than expected car recognition.

How do these results compare with prior group studies? Given the rarity of acquired prosopagnosia, most of these have been conducted with the developmental form. There was heterogeneity in the original report of the Old/New Tests in 7 subjects with developmental prosopagnosia (Duchaine & Nakayama, 2005). Subjects had reduced discrimination particularly for cars and guns, as well as long reaction times. The test has since been applied to others. Two of three subjects showing normal A' on all of four tests, but reaction time was not reported (Lee et al., 2010), while another found impairments on cars and/or guns in 10 family members, with 5 of 7 subjects impaired on cars at an individual level (Duchaine et al., 2007). Others have created similar tests, with one study finding normal recognition and reaction times for shoes in 16 subjects (Stollhoff et al., 2010) and another finding normal discrimination and reaction times for shells and novel objects in 21 subjects (Esins, Schultz, Wallraven, & Bulthoff, 2014), at least at a group level. One of eight children was impaired on an Old/New Test of flower recognition (Dalrymple et al., 2014).

While only two studies have applied the Cambridge Bicycle Memory Test (Biotti & Cook, 2016; Dalrymple et al., 2014), numerous studies have used the Cambridge Car Memory Test (Dennett et al., 2012) in developmental cohorts ranging from 9 to 20 subjects (Biotti & Cook, 2016; Biotti et al., 2017; Esins et al., 2016; Gerlach et al., 2016; Rivolta, Lawson, & Palermo, 2017; Shah, Gaule, Gaigg, Bird, & Cook, 2015a; Tanzer, Weinbach, Mardo, Henik, & Avidan, 2016), as well as one case study (Weiss et al., 2016). With the caveat that all of these studies had control groups of modest size, these have generally found normal results at the group level with one exception (Gerlach et al., 2016). At a single subject level five subjects were impaired across three studies with 35 subjects in total (Gerlach et al., 2016; Rivolta et al., 2017; Shah et al., 2015a), while three of 12 were borderline in another (Tanzer et al., 2016). In one group the performance of controls with cars was too poor to allow identification of impaired single subjects (Biotti & Cook, 2016; Biotti et al., 2017); however, none of the subjects was impaired on the Cambridge Bicycle Memory Test (Biotti & Cook, 2016). All of eight prosopagnosic children scored normally on the latter as well (Dalrymple et al., 2014). Only one study (Esins et al., 2016) provided individual data for both controls and prosopagnosic subjects to allow us to analyze the difference between face and car scores: this showed a putative classical dissociation in three of 16 subjects (subjects 9, 11 and 14). Some of these studies could be criticized for not having strict diagnostic criteria for prosopagnosia, such as lax statistical limits of 1.65–1.75 standard deviations (Palermo et al., 2017; Tanzer et al., 2016) or reliance on a subjective questionnaire (Esins et al., 2016).

Thus these findings with Old/New Tests and the Cambridge Bicycle or Car Memory Tests are similar to the results of our developmental cohort: generally normal performance at a group level with a few subjects performing below a criterion of 2 standard

deviations, but on the other hand only half or less showing a putative classical dissociation.

The potential role of expertise has long motivated studies of subjects with acquired prosopagnosia on objects of their own circumscribed interests, with mixed results, as well as one recent case of developmental prosopagnosia (Weiss et al., 2016). It also lies behind studies that trained prosopagnosic subjects to acquire expertise with artificial objects such as greebles (Behrmann, Marotta, Gauthier, Tarr, & McKeeff, 2005; Bukach et al., 2012; Duchaine, Yovel, Butterworth, & Nakayama, 2006; Rezlescu, Barton, PItcher, & Duchaine, 2014). However, expertise is a subject characteristic that lies on a spectrum, and no study has attempted to match objectively the expertise of control subjects with that of the case. As for group studies, few if any have performed an expertise-adjusted assessment of object recognition. One study administered a short visual car identification test as an index of car expertise, results of which they used to adjust the scores on the Cambridge Car Memory Test (Esins et al., 2016). However, this fails to consider the possibility that scores on a visual car identification test may themselves reflect the prosopagnosic disorder, rather than just gauging the subject's interest and experience. In that sense, the reduced car identification in four of their 16 subjects could actually point to an object recognition problem, without the type of non-visual expertise-adjustment we performed.

This would then be similar to other studies that have probed long-term object familiarity or identification without adjusting for expertise. The ability to name cars was normal in one study of 6 subjects (Dobel, Bolte, Aicher, & Schweinberger, 2007). Identifying a pre-specified exemplar of flowers, birds or cars was impaired in one group of 64 subjects (Zhao et al., 2016) but intact in another group of 17 (Song, Zhu, Li, Wang, & Liu, 2015b). The data of the former have been analyzed elsewhere at a single-subject level (Geskin & Behrmann, 2018). Concerns have been raised that this test was too easy (Geskin & Behrmann, 2018), and that the diagnostic criteria for prosopagnosia was somewhat lax, relying on a questionnaire and a score 1 standard deviation below the control mean on an Old/New Test of face familiarity (Zhao et al., 2016).

Our car recognition test required subjects to recognize 150 exemplars and performed an expertise-adjustment using non-visual semantic information that should not be affected by prosopagnosia. Both of these features may have contributed to the greater sensitivity of this test in detecting subtle object recognition deficits in our prosopagnosic cohorts. If the problem with object recognition in prosopagnosia is not simply a matter of within-category recognition, but of expert-level performance of such recognition, then the best evidence regarding the status of object recognition would come from subjects who have greater expertise with that type of object. Our results show that 7 of 10 subjects who were relatively expert with cars showed impaired car recognition, but three did not.

It has been claimed that demonstrations of impaired car expertise in prosopagnosic patients in prior reports may not be valid because basic object recognition problems were not excluded (Rossion, 2018a). While none of our patients displayed the types of object recognition deficits seen in general visual agnosia, it is true that a few subjects with acquired prosopagnosia had difficulties on the visual object and space battery, e.g., B-ATOT3 (Table 3). Those with developmental prosopagnosia rarely had difficulty with this battery, though (Table 4). Furthermore, one could consider good performance on the Old/New Tests and the Cambridge Bicycle Test as even stronger evidence of intact basic-level object recognition. In this regard, R-IOT4 and R-AT2 are of interest: both were normal on all aspects of the visual object and space battery, both had normal accuracies on the four Old/New Tests (the only abnormality was a slightly elevated reaction time on one of the four tests in R-IOT4), and both showed a firm putative classical dissociation in the Cambridge Bicycle Test. Nevertheless, both were car experts and demonstrated severe deficits for expertise-adjusted visual car recognition (z-score of −8.78 for R-IOT4 and −5.76 for R-AT2). The same could be said for subjects DP008 and DP016. These four subjects thus provide good evidence of impaired expertise-adjusted car recognition with otherwise good object recognition. This provides an interesting parallel to conclusions from factor analysis work in healthy subjects that there may be separate processes for faces and cars that are both distinct from general object mechanisms (Cepulic et al., 2018; Richler et al., 2017).

Our results are consistent with a main conclusion of the review by Geskin and Behrmann (Geskin &

Behrmann, 2018), that there are examples of both association and dissociation of deficits in object and face recognition in developmental prosopagnosia. One of the challenges for any model of the recognition impairment in prosopagnosia is to explain the presence of both associations and dissociations. Some have stressed that dissociations are more theoretically informative in neuropsychological cases (Gray & Cook, 2018; Towler & Tree, 2018). While there can be many reasons for associations, a dissociation would be good evidence of independent mechanisms. However, there are methodologic issues that must be considered before accepting an apparent dissociation as real.

One point is the criteria for a putative classical dissociation (Gerlach et al., 2018; Shallice, 1988). On these more stringent grounds, half of our prosopagnosic subjects showed a dissociation between bicycle and face test scores. However, this still did not prove that all object recognition is intact, as several subjects with a dissociation showed abnormalites on the Old/New Tests or on expertise-adjusted car recognition. A second point is whether the object tests used are easier than face tests. It may be that faces resemble each other more than do cars, horses or guns, which would render object discrimination tests easier and lead to spurious dissociations (Campbell & Tanaka, 2018). Accuracy rates in controls can serve as a behavioural index of discriminability: our control data showed that the Cambridge Bicycle Memory Test is at least as difficult as the Cambridge Face Memory Test. Third, the decisional space is also a potential difference between objects and faces (Ramon, 2018). While it may be difficult to find another category that is as densely populated with exemplars as face space, the potential model space for cars is in the low thousands, and a car expert may thus have a decision space that is reasonably large.

If we accept face-object dissociations in even a few prosopagnosic subjects as real – and we would suggest that subject DP033 has the strongest evidence for intact object recognition – then how do we explain the fact that other subjects have evidence for impaired object recognition, particularly at an expert level? Several have advanced potential reasons for why face and object recognition may show both associations and dissociations.

One position is simply to dismiss those with evidence of object recognition impairments as not having prosopagnosia (Rossion, 2018a), but some other form of object agnosia, even if this is not as severe as in typical cases of general visual agnosia. This makes the question about object impairments in prosopagnosia tautological, since the finding of some other deficit automatically invalidates the diagnosis. Our survey would also suggest that this would limit the label of prosopagnosia to a handful of patients. This position may be tenable if it could be shown that the mechanism of impaired face recognition in those with normal object recognition differed from those in whom tests revealed some object impairments, but it is not yet clear if this is the case.

For the developmental variant, the "independent disorders hypothesis" proposes that whether a patient has a selective disorder or not reflects the variable severity of a common developmental failure affecting face, body and object perception, possibly involving a structure like the inferior longitudinal fasciculus (Gray & Cook, 2018), or possibly more anatomically widespread problems (Jiahui, Yang, & Duchaine, 2018). This resembles the older argument about acquired prosopagnosia, that associations can reflect the propensity of large-scale pathology to affect adjacent but distinct networks for face and objects, with occasional dissociations when the lesion is more selective by an accident of anatomy (Barton & Corrow, 2016c; Garrido et al., 2018). By such accounts, dissociations – even if rare – are more valuable than associations to the theoretical position, as proof that a face-specific perceptual substrate exists (Garrido et al., 2018). On the other hand associations – especially if frequent – are important to understanding the potential anatomic and/or pathologic links between face and object processing, as well as the experience of the majority of subjects with the disorder.

Given hierarchical concepts of visual processing, others postulate that associations could arise from damage to domain-general stages of either low-level sensory processing or high-level cognitive functions of memory and intelligence, while face-selective deficits arise from lesions to intermediate face-specific stages (Eimer, 2018). This points to the importance of excluding general visual and memory deficits (Barton, 2018).

A speculation in developmental prosopagnosia is that hyperconnectivity between the lateral occipital

and inferior temporal regions is a marker of a visual compensation that recruits use of object processing areas for face recognition (Rosenthal & Avidan, 2018). If so, this could lead to an association between object and face processing abilities that will vary with the degree of compensation. A similar point is reflected in the suggestion that residual face processing in prosopagnosia may rely on more general perceptual mechanisms, and hence share a common fate with object perception (Towler & Tree, 2018). Also related is the assertion that associations between face and object deficits in a developmental disorder may not be as informative about normal brain anatomy as similar results in an acquired disorder, as one could speculate that failure to generate a modular organization is one consequence of the developmental failure (Rossion, 2018b; Starrfelt & Robotham, 2018) – but see (Jiahui et al., 2018).

Finally, others have suggested that visual regions may differ in selectivity, with "upstream" areas less selective than "downstream" visual areas (de Gelder & Van den Stock, 2018). Along these lines, our results with the Old/New Tests in acquired prosopagnosia suggest that deficits in short-term familiarity with other objects are more frequent with occipitotemporal than with anterior temporal lesions. This may be particularly true with bilateral posterior lesions, though our sample is too small to be definitive. However, we did not find a similar anterior-posterior difference for expertise-adjusted car recognition. One possible interpretation is that more basic within-category processing of objects relies on occipitotemporal function, while expertise also recruits anterior regions. If so, one might speculate that the generally normal performance on the Old/New Tests in our developmental prosopagnosic cohort implies a resemblance to acquired prosopagnosia from anterior temporal lesions. This recalls reports of altered connectivity from occipital to anterior temporal regions in developmental prosopagnosia in some studies (Avidan et al., 2014; Thomas et al., 2009) – though others have found that white matter anomalies are more limited to the fusiform region (Gomez et al., 2015; Song et al., 2015a). However, generalizing from acquired to developmental prosopagnosia requires caution: it is not logically necessary that intact object recognition in developmental prosopagnosia has the same explanation as intact object recognition in acquired prosopagnosia.

Some have proposed that additional evidence of a common mechanism for faces and objects would be a correlation between face and object processing scores (Geskin & Behrmann, 2018; Gray & Cook, 2018), though others argue that correlations may reflect general performance factors involved in the task, such as general cognitive speed, memory, learning or interference effects (Eimer, 2018; Richler, Floyd, & Gauthier, 2015). Our results did not confirm a relationship between the Cambridge Face Memory Test scores and aggregate car/gun scores on the Old/New Tests. While there was a modest correlation between the Cambridge Bicycle and Face Memory Tests in our large sample of control subjects, the correlation was not significant in the combined prosopagnosic cohort. Failure to find a correlation in a cohort of this size does not prove its absence: confidence in such a null result would require a much larger sample of developmental prosopagnosic subjects.

There are a number of limitations to this study. The number of prosopagnosic subjects was small. As acquired prosopagnosia is rare, though, this is likely the largest cohort in whom object recognition has been studied. Also, though a strength of our study was the application of a considerable number of tests, which allowed us to address each of the 11 points listed in Table 1, the corresponding weakness was that not all subjects were able to complete all tests. The Old/New Tests uses the same stimuli at the recall and study phases, and so, even though this is a memory rather than a discrimination test, low-level image matching may play a role in performance. Thus it may underestimate the frequency of object recognition deficits. The expertise-adjusted test of car recognition was more sensitive, but the weak point of this test is the inability to make inferences about single subjects who are not car experts. In some ways, though, that is the point: one cannot conclude anything about expert processing in subjects who aren't expert. Rather, one of the strengths of the group linear regression analysis of this test is examining how visual recognition changes with increasing car expertise, with results showing that both developmental and acquired groups show half the normal gains in visual car recognition for each increment in expertise.

In summary, we find that basic within-category object familiarity is often normal in developmental prosopagnosia, but impaired in acquired

prosopagnosia from occipitotemporal lesions. Both cohorts showed present but reduced expertise effects in car recognition, and impaired car recognition was present in the majority of subjects who were more expert with cars. Also, some of these subjects performed well on our other tests, suggesting that impaired car recognition could not be blamed on more basic problems with object recognition. Nevertheless, at least one and possibly two subjects with developmental prosopagnosia met very stringent requirements for intact object recognition on all tests. Hence our study provides some support for the conclusions of a large review (Geskin & Behrmann, 2018), that a minority of subjects with developmental prosopagnosia have good evidence for intact object processing, but the majority do not. In that majority, reduced expertise effects proved in our study to be a sensitive means of detecting recognition deficits for some non-face objects in prosopagnosia. Although it requires more extensive protocols, expertise-adjustment may be an important factor in detecting or excluding subtle object recognition deficits in prosopagnosia.

Notes

1. As an example, our control subjects had a mean score of 37.17 on the Cambridge Bicycle Memory Test, while the linear regression of their scores against age had a slope of 0.08 and an intercept of 35.05. Prosopagnosic subject R-IOT1 was age 49 and his score was 37. His age-predicted score would be 35.05+0.08*49 = 38.90. Hence his deviation from predicted score is 37 – 38.90 = −1.90. To create an age-adjusted score we add this deviation to the control mean performance: −1.90 + 37.17 = 35.27.
2. Here and in the discussion, dissociations on the Cambridge Bicycle Memory Test are considered present only if both the analytic methods we used indicated this.

Disclosure statement

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