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Perceptual Learning of Faces: A Rehabilitative Study of Acquired Prosopagnosia

Jodie Davies-Thompson^{1,2}, Kimberley Fletcher^{1,3}, Charlotte Hills¹, Raika Pancaroglu¹, Sherryse L. Corrow¹, and Jason J. S. Barton¹

Abstract

■ Despite many studies of acquired prosopagnosia, there have been only a few attempts at its rehabilitation, all in single cases, with a variety of mnemonic or perceptual approaches, and of variable efficacy. In a cohort with acquired prosopagnosia, we evaluated a perceptual learning program that incorporated variations in view and expression, which was aimed at training perceptual stages of face processing with an emphasis on ecological validity. Ten patients undertook an 11-week face training program and an 11-week control task. Training required shape discrimination between morphed facial images, whose similarity was manipulated by a staircase procedure to keep training near a perceptual threshold. Training progressed from blocks of neu-

tral faces in frontal view through increasing variations in view and expression. Whereas the control task did not change perception, training improved perceptual sensitivity for the trained faces and generalized to new untrained expressions and views of those faces. There was also a significant transfer to new faces. Benefits were maintained over a 3-month period. Training efficacy was greater for those with more perceptual deficits at baseline. We conclude that perceptual learning can lead to persistent improvements in face discrimination in acquired prosopagnosia. This reflects both acquisition of new skills that can be applied to new faces as well as a degree of overlearning of the stimulus set at the level of 3-D expression-invariant representations. ■

INTRODUCTION

Face recognition is an important skill in daily life. Prosopagnosia, the inability to recognize familiar faces, can negatively affect the quality of life (Yardley, McDermott, Pisarski, Duchaine, & Nakayama, 2008). Although its natural history has been documented infrequently (DeGutis, Chiu, Grosso, & Cohan, 2014), the chronicity of cases in the literature suggests that it tends to persist after a permanent lesion; therefore, interventions that can ameliorate face recognition deficits would be welcome. However, despite the large number of studies on prosopagnosia, few attempts have been made at improving face recognition in this condition.

A review of the literature reveals 10 reports of training in acquired prosopagnosia, all single cases (Table 1). These vary not only in patient characteristics but also in the intensity of training, the evaluations performed, and the results. The types of training varied as well. As others have noted (Bate & Bennetts, 2014; DeGutis, Chiu, et al., 2014), these can be classified as strategic compensations, in which training is directed at improving recognition through a route that circumvents or substitutes for the damaged process, and remedial approaches, which try to restore or improve the damaged process. Face training approaches can also be divided into mnemonic and

perceptual strategies: Whether these are strategic or remedial depends partly on whether the patient has an associative/amnesic or an apperceptive variant of prosopagnosia (Davies-Thompson, Pancaroglu, & Barton, 2014; Barton, 2008).

Mnemonic approaches have included use of the visual tricks of professional mnemonists to enhance identification of specific people (Francis, Riddoch, & Humphreys, 2002; Wilson, 1987), improving learning of faces by linking them to names and/or semantic data (Powell, Letson, Davidoff, Valentine, & Greenwood, 2008; Polster & Rapcsak, 1996; Ellis & Young, 1988), and attempts to translate covert semantic effects into overt recognition (De Haan, Young, & Newcombe, 1991). Perceptual approaches include those that train patients to explicitly attend to facial features (Powell et al., 2008; Mayer & Rossion, 2007; Polster & Rapcsak, 1996; Beyn & Knyazeva, 1962), which are classified by some as strategic compensations in that feature recognition is substituting for normal whole-face recognition, and those that have the remedial aim of improving perceptual discrimination of faces (Bate et al., 2015; DeGutis, Cohan, Kahn, Aguirre, & Nakayama, 2013; Ellis & Young, 1988). All of these approaches have examples of positive and negative training effects.

How outcomes were evaluated also varied in these studies, which naturally leads to consideration of what would be the desirable properties of a training effect in this condition. First, if training improves recognition of

¹University of British Columbia, ²University of Nottingham, ³Derby Hospitals NHS Foundation Trust

Table 1. Prior Studies of Training in Acquired Prosopagnosia

Report	Wilson 1987		Ellis 1988		de Haan 1991	Francis 2002	Powell 2008	Polster 1996	Behrmann 2005	Mayer 2007	Leone 2008
Subject	OE	KD			PH	NE	WJ	RJ	SM	PS	CL
Age, sex	27, male	4, female			22, male	21, female	66, male	68, male	24, female	56, female	40, female
Duration (years)	2.5	3			3	2	17	6	6	14	1
Lesion	T	?			OT	T	OT	OT	O, T	OT	OT
Hemisphere	right	?			bilateral	right	bilateral	right	right	bilateral	right
Cause	trauma	meningitis			trauma	encephalitis	stroke	stroke	trauma	trauma	stroke
Subtype	apperceptive	apperceptive			apperceptive	associative semantic	apperceptive	apperceptive	apperceptive	apperceptive	apperceptive
Other	amnesia neglect	object agnosia							object agnosia		
Training	mnemonic	perception	name association	semantic context	mnemonic, semantic	feature attention	semantic	Greeble	feature attention		
Trials/session		50	8			60	22	190			
Minutes/session					2						
Number of trials	275										
Number of sessions		72	11		7	1	1	31			
Number of months	2	13			0.5			4			
Control task					untrained set	rehearsal set	simple exposure	feature attention			
Effect on faces	none	none	none		identification	identification	familiarity	familiarity	increased latency	identification	identification
Generalization						yes		no			
Transfer					n/a	n/a					
Maintenance (time)					no, 2 months	yes, 1 week		yes, 20 min			
Daily life										confidence	
Other assessments								fMRI			

n/a = not applicable; O = occipital; OT = occipitotemporal; T = temporal.

the same pictures of the same faces used in training, this may not translate to benefit in daily life where changes in view, lighting and expression can rapidly alter the 2-D image of the face. For training to have ecological validity, learning should improve recognition despite such variations, which we term “generalization.” Generalization indicates that learning is occurring at the level of 3-D identity representations that are robust to variations in expression. Second, it would be desirable if training transferred to new faces. Lack of transfer may indicate that training is resulting in overlearning of a set of stimuli with existing skills, whereas the presence of transfer would be evidence of development of a new skill. Transfer, however, is not usually an aim of mnemonic methods, which promote recall of specific faces rather than all faces. Transfer in this setting only has meaning in the sense that the method can be applied to new faces, though patients generally have found this cumbersome and impractical in real life (Francis et al., 2002). Third, improvements should persist after a period without training. Finally, it would be helpful to show that benefit does not occur with a control task, to ensure that effects are not due to general factors such as increased engagement with faces or interactions with investigators.

In this report, we describe a remedial perceptual learning approach, which incorporates elements in training design and assessment with these desirable characteristics in mind. Perceptual learning is the improved response of sensory systems to stimuli that is gained through experience, typically repetitive practice of specific sensory tasks (Ahissar & Hochstein, 2004). Such learning has been shown to occur for many low-level features such as orientation (Schoups, Vogels, & Orban, 1995), motion direction (Ball & Sekuler, 1987), depth (Fendick & Westheimer, 1983; Ramachandran & Braddick, 1973), and segmentation from textural cues (Gilbert, Sigman, & Crist, 2001; Karni & Sagi, 1991). Perceptual learning has also been used to improve discrimination of complex shapes, such as novel objects called “Greebles” (Gauthier & Tarr, 1997), even in a patient with visual agnosia (Behrmann, Marotta, Gauthier, Tarr, & McKeef, 2005). The potential of a perceptual learning approach is reinforced by reported benefits when patients with developmental prosopagnosia are trained to classify faces by the spatial relationships between features (DeGutis, Cohan, & Nakayama, 2014; DeGutis, Bentin, Robertson, & D’Esposito, 2007), although this benefit was not seen in a patient with acquired prosopagnosia (DeGutis et al., 2013). Nevertheless, another perceptual learning program resulted in some benefits in EM, who also had acquired prosopagnosia (Bate et al., 2015).

In the current study, we used a morphing program to create facial stimuli that varied systematically in many aspects of shape across the entire face. Given a purported shift toward holistic face processing as a face becomes familiar (Tanaka & Sengco, 1997; Farah, Wilson, Drain, & Tanaka, 1995; Tanaka, 1993; Young, Hellawell, & Hay, 1987) and the possibility that prosopagnosia is char-

acterized by some deficiency in holistic face perception (Ramon, Busigny, & Rossion, 2010; Van Belle, De Graef, Verfaillie, Busigny, & Rossion, 2010; Sergent & Signoret, 1992; Sergent & Villemure, 1989), training with such stimuli may encourage development of a holistic skill in face recognition. Second, our training blocks varied the view and expression across faces being matched. This may focus learning on both 3-D facial shape and the structural properties that encode a stable identity across changes in expression. Third, we applied training to a cohort of 10 patients rather than one patient: The anatomic and functional variations of prosopagnosia (Davies-Thompson et al., 2014; Barton, 2008) make it difficult to extrapolate from a single case to all other patients. Finally, we incorporated a control task and designed evaluations that assessed for generalization, transfer, and maintenance of benefit.

METHODS

Participants

We recruited 10 participants with acquired prosopagnosia (Table 2), many from the Web site www.faceblind.org. Diagnostic criteria included (a) subjective complaints of impaired face recognition in daily life after the onset of the neurological lesion, (b) impairment on a test of famous face recognition (Barton, Cherkasova, & O’Connor, 2001), and (c) impairment on at least one of either the Cambridge Face Memory test (Duchaine & Nakayama, 2006) or the faces component of the Warrington Recognition Memory test (Warrington, 1984)—we note that most scored poorly on both—while performing normally on the word component of the latter (Table 3).

Exclusion criteria included psychiatric disorders, degenerative disorders of the central nervous system, best-corrected visual acuity less than 20/60, general visual agnosia or amnesia, as assessed on a neuropsychological battery (Table 3). All were English-speaking, white, and from the United States or Canada. MRI contraindications included pacemakers, ear implants, metallic foreign bodies, other types of MRI-incompatible metal or electrical devices, or pregnancy. Informed consent was obtained from the institutional review board of the University of British Columbia, and all participants gave informed consent in accordance with the principles of the Declaration of Helsinki.

Before training, participants had 5 days of initial characterization and baseline testing. These included a neuro-ophthalmologic history and examination, with Goldmann perimetry and Farnsworth–Munsell 100-hue test. Participants completed a neuropsychological battery assessing general intelligence, attention, handedness, object recognition, visual-perceptual abilities, and memory, and face processing was assessed with tests of face perception, short-term memory for faces, memory for famous faces, and face imagery (Table 3). They also had tests of name

Table 2. Participant Information

Participant	Age (years)	Handedness	Duration (years)	Lesion	Sex	Fields	Color FM-100	Medications	<i>fMRI Results</i>					
									OFA		FFA		STS	
									R	L	R	L	R	L
R-IOT1	55	left	18	hemorrhage	M	LUQ	normal	atenolol	x	–	x	–	–	–
R-IOT4	60	right	4	infarct	M	LUQ	impaired	simvastatin	–	–	x	–	–	–
								aspirin						
								niacin						
								triamterene						
								hydrochlorothiazide						
L-IOT2	60	ambidext	19	resection	M	full	impaired	phenytoin	–	–	x	x	–	–
								gabapentin						
								clonazepam						
								lacosamide						
								minocycline						
								escitalopram						
								desmopressin						
B-IOT2	60	right	44	trauma	M	RHH, LUQ	impaired		–	x	x	x	–	–
B-ATOT2	23	right	13	encephalitis	F	full	impaired		–	–	x	–	–	–
B-ATOT3	15	right	5	encephalitis	M	LHH	impaired	levetiracetam	x	x	x	x	x	–
R-AT3	41	right	11	encephalitis	M	full	normal	amphetamine	–	–	–	–	–	–
R-AT5	61	right	32	tumour	F	full	normal	lamotrigine	–	–	–	–	x	–
								atorvastatin						
								ropinorole						
								clopidogrel						
								fenofibrate						
								esomeprazole						
								aspirin						
B-AT1	31	right	10	encephalitis	M	full	normal		–	–	–	–	–	–
B-AT2	48	right	24	trauma	F	full	normal		–	–	–	–	–	–

FM-100 = Farnsworth–Munsell 100-hue test; F = female; L = left; LUQ = left upper quadrantanopia; M = male; R = right; RHH = right hemianopia; LHH = left hemianopia; OFA = occipital face area; FFA = fusiform face area; x = region absent on fMRI.

and voice processing, results of which have been published (Liu, Pancaroglu, Hills, Duchaine, & Barton, 2016): This showed that participants B-AT1 and B-AT2 also had difficulties with familiarity for voices, indicating parallel deficits in face and voice recognition.

Participants had two structural MRI scans on a 3.0-T Phillips scanner: a whole brain T1-weighted echoplanar imaging sequence and a whole brain coronal fluid-attenuated inversion recovery sequence (Figure 1). Participants also had an fMRI scan using the HVEM dynamic face localizer (Fox, Iaria, & Barton, 2009) to determine which

areas of their core face network—namely, the fusiform face area, the occipital face area, and the posterior STS—had been eliminated by their lesion. Apart from participant B-ATOT3, these data have also been published elsewhere (Liu et al., 2016; Hills, Pancaroglu, Duchaine, & Barton, 2015) and are summarized in Table 2.

Timeline

All participants visited the laboratory on three occasions for assessments. On their first visit, participants were

Table 3. Neuropsychological Testing

<i>Participant</i>	<i>Max</i>	<i>R-IOT1</i>	<i>R-IOT4</i>	<i>L-IOT2</i>	<i>B-IOT2</i>	<i>B-ATOT2</i>	<i>B-ATOT3</i>	<i>R-AT3</i>	<i>R-AT5</i>	<i>B-AT1</i>	<i>B-AT2</i>
<i>Attention</i>											
Trails A	-	39	48	54	80	30	41	22	43	18	30
Trails B	-	61	102	117	142	93	114	37	78	25	40
Star Cancellation	54	54	54	53	53	54	53	54	54	54	54
Visual Search	60	54	-	60	56	59	56	59	52	59	56
<i>Memory</i>											
Digit span-forward	16	12	8	10	14	7	10	16	10	12	9
Spatial span-forward	16	9	10	10	8	8	8	12	6	10	9
Word list	48	28	37	27	35	27	29	31	24	27	23
<i>Visuoperceptual</i>											
Hooper Visual Organization	30	27	22	9	22.5	12	6.5	27.5	22	20	28
Benton Judgment of Line Orientation	30	29	24	23	29	22	26	30	21	28	28
<i>Visual Object and Spatial Perception</i>											
Object: Screening	20	20	18	20	20	20	19	20	17	20	20
Incomplete Letters	20	19	19	17	19	19	17	19	20	19	19
Silhouettes	30	21	18	3	12	4.5	2	22	19	10	25
Object Decision	20	16	19	13	14	10	8	17	14	16	18
Progressive Silhouettes	20	9	13	10	15	4	20	11	17	17	8
Spatial: Dot Counting	10	10	9	10	10	9	9	10	10	10	10
Position Discrimination	20	20	19	19	19	15	14	19	18	19	20
Number Location	10	10	10	10	10	8	6	10	10	10	10
Cube Analysis	10	10	10	10	10	9	NC	10	8	10	9
<i>Imagery</i>											
Mental Rotation	10	10	10	7	10	10	10	10	10	10	5
<i>Face Processing</i>											
BFRT	54	45	46	31	38	37	28	38	33	45	40
Familiarity: Famous faces d'	-	1.96	1.29	0	1.31	-0.15	-0.8	0.9	1.52	-0.36	0.68
WRMT face	50	33	39	27	21	19	26	31	28	27	31
WRMT word	50	41	50	42	42	39	48	47	46	45	46
CFMT	72	44	27	21	24	24	28	31	35	30	31
Face imagery	100	82	84	41	86	48	60	49	81	*	50
<i>Name Processing</i>											
Familiarity	100	100	95	95	100	90	65	100	95	65	100
Occupation sorting	100	100	98	88	100	73	71	98	100	54	100

BFRT = Benton Face Recognition Test; CFMT = Cambridge Face Memory Test; WRMT = Warrington Recognition Memory Test. Values in **bold** type are abnormal results.

*Patient recognized too few names on the list for the test to be valid.

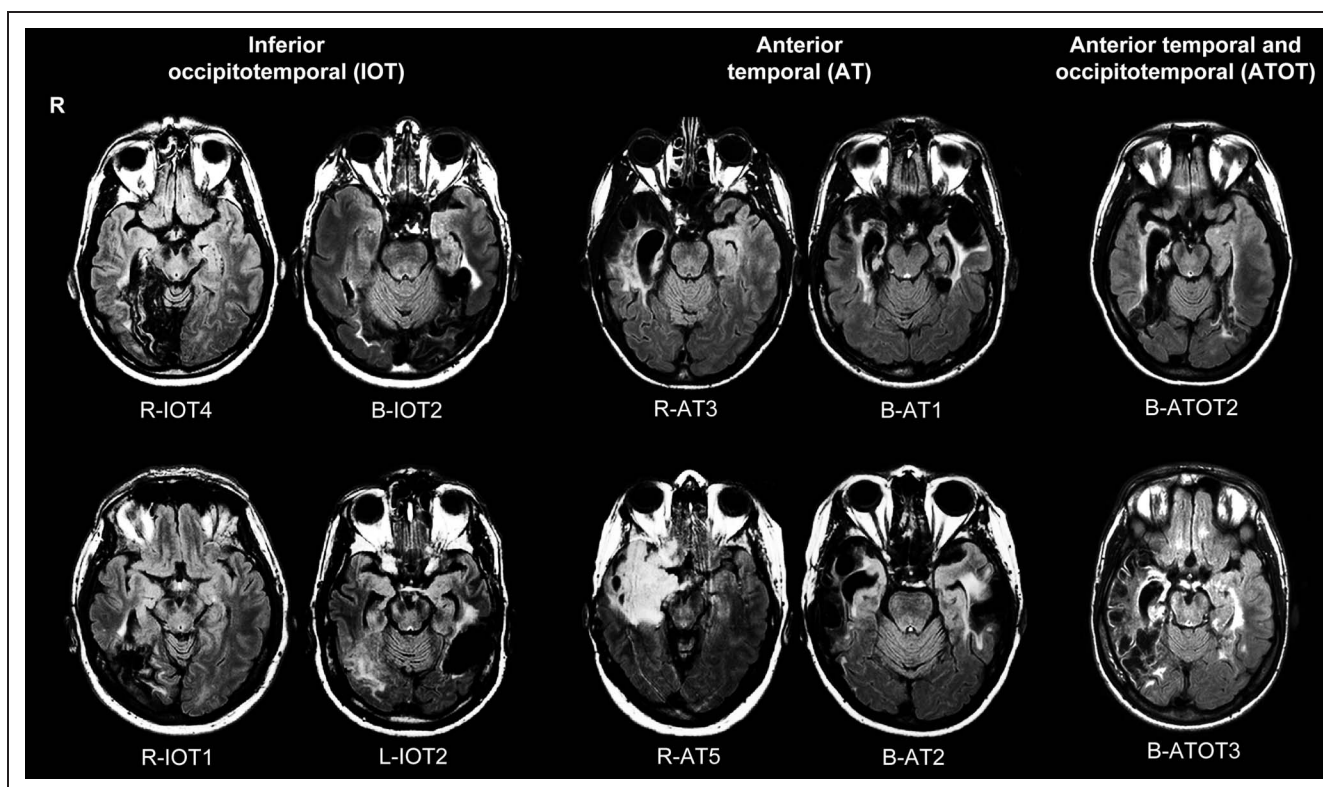


Figure 1. Structural MRI scans, FLAIR sequence, of the 10 prosopagnosic patients. The participants were paired by lesion similarity as shown in columns, with the top row showing the participants who did training first and the bottom row those who did the control task first.

introduced to the online training platform that also hosted the six online assessments and completed the first of these six online assessments during their visit. Participants completed the remaining five online assessments at home over 1 week, with no more than one per day. After the initial assessment, participants performed either the training or the control task. Participants were paired based on the similarities of their lesions (Figure 1), with one participant in the pair doing training first, and the other the control task first. Both the training and the control task took approximately 11 weeks. Following completion of training or the control task, participants then completed the second assessment. This consisted of the same six online assessments, which they completed before returning to the laboratory the following week for 3 days of neuropsychological and neuroimaging assessments. Participants then returned home and completed whichever of the training or control task they had not yet done. Finally, participants then performed the six online assessments in the week before returning to the laboratory for the final 3-day visit, during which they repeated the neuropsychological and neuroimaging assessments.

Face Training Protocol

The Face Training program (www.hvelab.org/facetraining) is an online program designed and built by the

HVEM laboratory that allows users to train on their own computers in their own homes. Experimenters can assign any given number of sessions to a participant, with a new training session made available to the user on completion of the previous session. The experimenter monitors each participant's progress at a distance, with results from a session available to the experimenter immediately after completion. All training and online assessments were performed on this system with each participant having their own account, allowing multiple participants at different stages to train in parallel.

Stimuli

We photographed 12 white men without facial hair in a local photography studio. Lighting was held constant across all photographs and models. Models were photographed at five angles of lateral rotation (0 = frontal view, 10°, 20°, 30°, 40°) and five expressions (neutral, happy, sad, angry, surprised), resulting in 25 images of each of the 12 men. External features (ears and hair) and distinguishing features (moles, etc.) were removed with Adobe Photoshop CS5.1 (www.adobe.com). Images were converted to grayscale and luminance-matched. Faces were unknown to all participants.

Next, we created images where the emotional expression varied in degree by morphing between one expression and the neutral face of the same person. Morphing

was done with Abrosoft FantaMorph 5 (www.fantamorph.com), with about 100 fiducial points around the features and outline of each of the two images to be morphed, resulting in gradual transition from one facial image to another. From the series of morphed images, we selected faces with 10% (i.e., 10% expressive and 90% neutral), 33%, 66%, and 100% expressive content for each emotional expression. This was repeated for each of the five viewing angles, resulting in a total of 85 faces for each of the 12 identities.

We then separated the 12 face identities into two sets of three pairs. Each participant trained on one set and the other set was used for testing with untrained faces. Thus five participants were randomly assigned to train on Set A, and the other four on Set B. Face pairs and face sets were equated approximately in discriminability, as determined by the following matching process. We presented five healthy participants with pairs of face images and asked whether the images were of the same person or not. These pairs had one image in 0° view with a neutral expression and the other in 30° view with a happy expression. All pairwise combinations in the set were used, creating 66 pairs. We showed each pair four times, for a total of 264 different and 264 same trials. The mean RT for the “different response” for each face pair was our index of similarity. We chose face pairs that were similar to another face pair in mean RT and assigned one pair to set A and one to set B.

Within a pair of two identities, corresponding images (e.g., the 10% angry faces in 0° view) were morphed between the first and the second person in increments of 2.5%, creating a gradual transition of one identity to an-

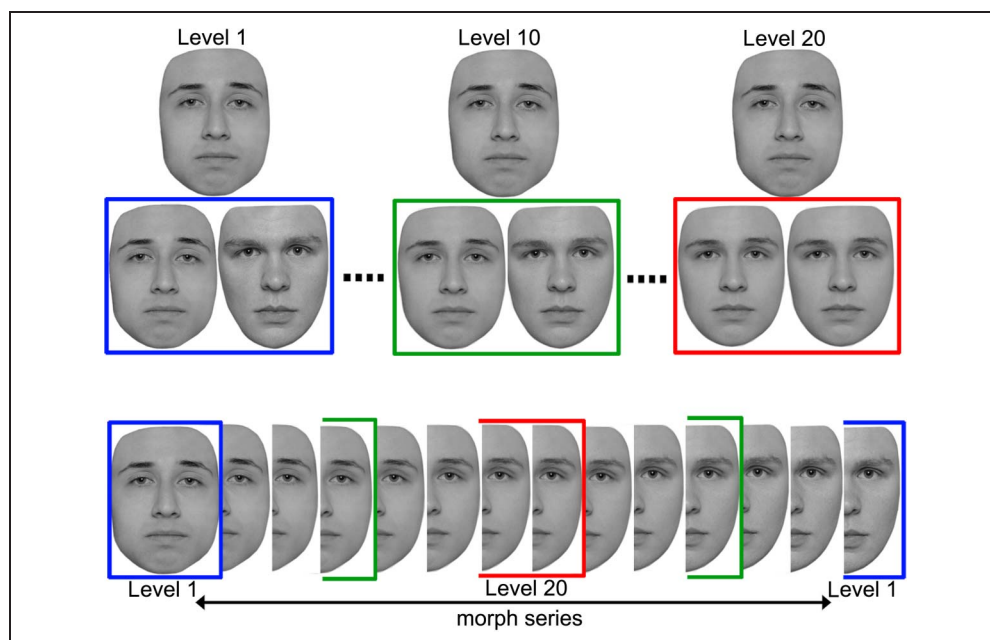
other (Figure 2). For a single image pair, this resulted in 40 morphed images. This process was repeated for each of the 85 base images for each of the six identity pairs.

Within-session Training Protocol

Each training trial presented three faces (Figure 2). The top face was always one of the original unmorphed images of a pair, in 0° view with a neutral expression. Below were two choice faces, and the task was to indicate with a keyboard press which of these two most resembled the top face. This method aimed at training perceptual rather than memory processes and shares design elements with the Philadelphia Face Similarity Test (Thomas, Lawler, Olson, & Aguirre, 2008) and another study of perceptual face training (Bate et al., 2015). The design reflected evidence from previous studies of perceptual learning of faces that suggested an advantage for simultaneous over sequential faces in discrimination tasks (Mundy, Honey, Downing, et al., 2009; Mundy, Honey, & Dwyer, 2007, 2009) and better perceptual learning for faces shown alongside similar rather than dissimilar faces (Dwyer & Vladeanu, 2009).

To reduce the chances of participants resorting to a serial feature-by-feature analysis instead of evaluating the whole face, the top face disappeared after 2 sec while the two choice faces remained until a response was made. To minimize low-level image matching, the size of the bottom two images varied randomly between trials, being 100%, 85%, or 70%, of the size of the top face. Such size variation may also enhance the benefits of training object recognition (Furmanski & Engel, 2000).

Figure 2. Example training trials (top) and selected images from a set of morphed stimuli of an identity pair (bottom). Participants see three faces and indicate which of the bottom two faces most resembles the top face. Difficulty was manipulated by creating a morph continuum of two face identity images (bottom): using as choice faces the images from the far ends of the morph series creates the easiest discrimination level (blue frame, Level 1). Pairing images at the center of the morph series creates the most difficult trial (red frame, Level 20), whereas pairing images located between the center and the end of the spectrum creates a moderately difficult trial (green frame, Level 10). A session begins with an easy Level 1 trial and a staircase procedure increases the difficulty level by one if they give a correct answer and decreases it by six if they give a wrong one.



To keep participants motivated, we provided feedback: A green tick appeared briefly on the screen after a correct response, but no feedback after an incorrect one.

The level of difficulty of a trial was determined by which pair of images from the morphed series were shown as the two choice faces (Figure 2). At the easiest level, Level 1, these were the unmorphed images from the ends of the morph spectrum. At the hardest level, Level 20, these were the two morphed images on either side of the center of the spectrum (47.5% of one identity and 52.5% of the other). A testing session began with the easiest level. A staircase design controlled the difficulty levels of subsequent trials. This followed the rules of an up-down weighting procedure (Kaernbach, 1991). To keep the participants training near their 85.7% correct perceptual threshold, we used a 1-down/6-up staircase: that is, a correct response resulted in the next trial increasing in difficulty by one level, while after an error the next trial decreased in difficulty by six levels. During training, the trials for the three identity pairs were presented in interleaved, independent staircases.

After participants had made either 12 reversals, 6 up and 6 down (Wetherill & Levitt, 1965), or correctly answered the highest difficulty level six times, they were then given another 200 training trials, with the staircase continuing to vary difficulty. This was done in parallel for each of the three pairs. Thus, participants performed 600 more trials after reaching threshold, with the entire session taking approximately 30–40 min. This amount of training is in the range of the duration or number of trials used by previous studies that obtained perceptual learning for faces, hyperacuity, and texture discrimination (DeGutis et al., 2007; Fahle & Morgan, 1996; Karni & Sagi, 1991). At the end of a session, participants were shown their average performance for that session as another form of feedback.

Between-session Training Protocol

Each participant completed three sessions each week. Participants were free to do them on any day they preferred. As sleep may help consolidate perceptual learning (Fenn, Nusbaum, & Margoliash, 2003; Gais, Plihal, Wagner, & Born, 2000; Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994), participants were asked to complete sessions in the early evenings and to do only one session per day. For each training block, participants performed a minimum of three repeated sessions and continued repeating sessions for that block until there was no further improvement. Improvement was defined as a more than 5% increase in performance threshold between two sequential sessions with less than a 5% increase in reaction time, so that this did not simply represent a speed-accuracy trade-off.

Completion of a block led to promotion to the next of a series of 11 blocks (Figure 3). In the first block, the two choice faces were presented with the same 0° view and neutral expression as for the top face. Subsequent blocks gradually introduced greater variations in view (Blocks 2–

4), in expression (Blocks 5–8), or in view for 100% expression (Blocks 9–11) in these choice faces, whereas the top face remained in 0° view with neutral expression. Expressions included happy, sad, and angry faces in 33%, 66% and 100% morphing increments, whereas views included 10°, 20° and 40° rotations from the frontal position. The 30° view and “surprised” expressions were not used in training but were reserved for testing as untrained stimuli. As participants reached the more difficult training blocks, they were making perceptual discriminations across substantial variations in view and expression, an important requirement in daily life. Adding these variations irrelevant to identity may also promote one hypothesized aspect of perceptual learning: learning to attend to detectors tuned to the most informative stimulus dimensions (Palmeri, Wong, & Gauthier, 2004). In addition, progressing from easy to difficult tasks may be an important feature of effective protocols for perceptual learning (Ahissar & Hochstein, 2004).

Control Task

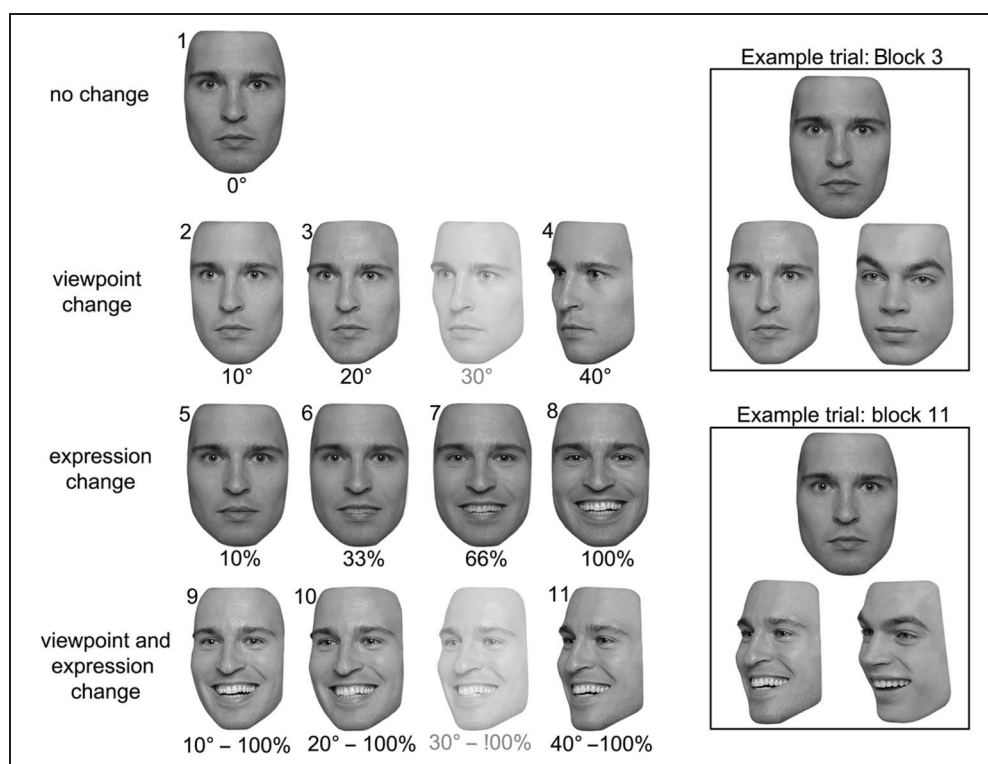
To determine if any benefits were due to the training program specifically or simply to enforced attention and exposure to faces, each patient did a control task. Patients watched episodes from a British television series of their choice (Midsomer Murders, Doc Martin, Taggart, Prime Suspect, Foyle’s War, or Cracker), which were chosen to ensure that patients were unfamiliar with either the faces of the actors or the names of the characters. Patients and a close relative confirmed their lack of prior knowledge about them. Duration of the control task was matched as closely as possible to that of the training, with each patient undergoing approximately 1.5 hr of watching episodes per week for 11 weeks. Their other television viewing was not regulated. To ensure that participants were paying attention while watching these programs, participants were asked six questions about the plots and events in the previous week’s episodes. All participants were able to answer a minimum of three questions correctly for each episode, with over 90% of queries being answered correctly.

Evaluation of Training Effects

Primary Outcomes

These used the same staircase procedure as training: The average level of the 12 reversals was their “perceptual sensitivity” to morphed changes, which we expressed as a percentage of the morph range (one level equals 5%). Assessments differed from training in that no feedback was given, all three faces remained on the screen until a decision was made, staircases were not followed by the added 600 training trials, and they included face identities from both set A and set B, only one of which had been used during training. There were six tests (Figure 4). The first two assessed benefits for views and

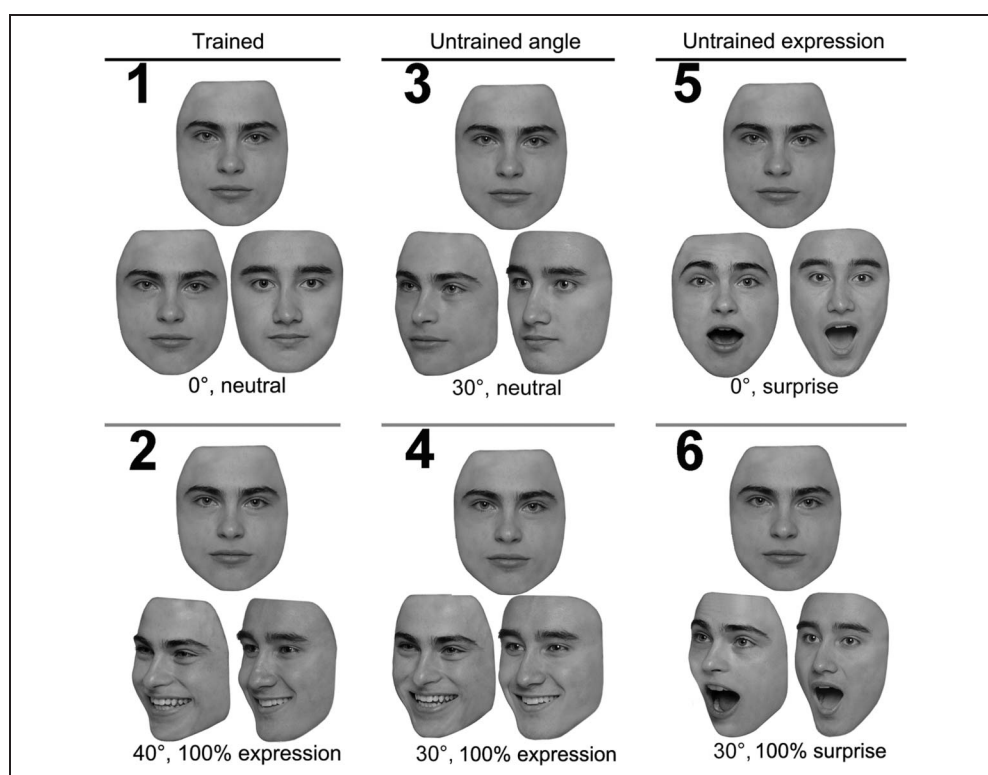
Figure 3. Example images of choice faces from the 11 different training blocks, as indicated by numbers. In Blocks 2–4, the view difference increases, in Blocks 5–8, the expression difference increases, whereas in Blocks 9–11, the view difference increases for the 100% expression face. Shown here are examples from a single emotional expression (happy), among the four used in training (neutral, happy, sad, angry). Faded images represent the view condition of 30° that was used only in assessments, not in training. A fifth expression (surprised) was also reserved for use in assessments only.



expressions seen during training. Test 1 showed the easiest training level (0° view, neutral expression), and Test 2 showed the most difficult level (40° view, 100% expression change). The next two tests assessed benefits for an untrained view, namely 30°. Test 3 presented this un-

trained view with the neutral expression, and Test 4 with 100% of trained expressions. The final two tests used the untrained expression of surprise. Test 5 showed this in 0° view, whereas Test 6 presented the untrained surprised expression with the untrained view of 30°. Participants

Figure 4. Example trials of the six online assessments. Tests 1 and 2 used views and expressions seen in training (old-image). Tests 3 and 4 used the untrained view of 30°. Tests 5 and 6 used the untrained expression of surprise (Test 6 also used the untrained view). One set of six assessments used the set of faces on which the participant trained, whereas the second set used the set not used in training.



completed all six test sessions within a week, with a maximum of two sessions separated by at least 1 hr on any given day. Tests were done in the same order at each assessment.

Secondary Outcomes

On each of their three visits to the laboratory, participants performed two tests of short-term familiarity for recently viewed faces, the Cambridge Face Memory Test (Duchaine & Nakayama, 2006), and the Warrington Recognition Memory test (Warrington, 1984). They also performed two tests that probed perceptual discrimination of faces, rather than familiarity. The first was the Cambridge Face Perception Test (Duchaine, Germine, & Nakayama, 2007). To eliminate learning effects and to stabilize their score, each participant completed the Cambridge Face Perception Test five times at each visit, with a maximum of three per day, and the average of the best two taken as their measure. Second, we tested participants on their ability to discriminate changes in feature shape and the spatial relations between features, such as interocular distance and the distance between the nose and mouth (Malcolm, Leung, & Barton, 2005): Such spatial relations are considered a type of configural information whose perception is particularly impaired in prosopagnosic participants with lesions of the fusiform face area (Barton, Press, Keenan, & O'Connor, 2002). To guard against experimenter bias, the person administering these tests was blinded to whether the participant had just done training or the control task.

Impressions of the Participants

Other training studies have asked participants to describe the effects of training on their experience with faces in daily life, to give a sense of ecological utility (Bate et al., 2015; DeGutis, Cohan, et al., 2014; Mayer & Rossion, 2007), and we did the same.

Analysis

Primary Outcomes

To determine if performance changed after an intervention (either training or the control task), we constructed a “percent change index” as our main outcome variable, by dividing the difference between perceptual sensitivity immediately before and after the intervention by their average, with a positive value indicating improvement. Thus, if the participant performed the control task first and the training task second, control effects were evaluated by comparing the first (baseline) and second assessments, whereas the training effect was evaluated by comparing the second and third assessments. As a check on our results, besides the relative improvement expressed in the percent change index, we also evaluated

the absolute change in performance by using a “difference score” as a second outcome variable. This was simply the difference between perceptual sensitivity before and after an intervention, as described above, without dividing by the average of the two.

For the online assessments, we compared three percent change indices. The first was for trained stimuli or “old-image,” combining the results of Tests 1 and 2. The second was for the untrained “new-view,” combining the results of Tests 3 and 4, and the third was for the untrained “new-expression,” combining the results of Tests 5 and 6. This was done for the set of faces used in training and the new untrained set of faces separately. We analyzed percent change indices with a repeated-measures ANOVA, with factors of face set (trained, untrained), testing condition (old-image, new-view, new-expression) and intervention (training, control task), with subject as a random effect.

To assess for generalization to new images of the trained faces, we first used one-sample *t* tests for the percent change indices for the old-image, new-view, and new-expression testing conditions separately to determine if there was an effect different from zero, from either training or the control task. We then examined a priori linear contrasts in the repeated-measures ANOVA to determine if the training effect was greater than the control effect for each of these three testing conditions, for the set of trained faces only.

To assess for transfer to new faces, we first used one-sample *t* tests for the overall percent change index, obtained by averaging over Tests 1–6 to determine if the effect was different from zero for either the training or the control task. This was done for trained and untrained faces separately. We then examined a priori linear contrasts in the repeated-measures ANOVA, first to determine if the training effect was greater than the control effect, for trained faces and then for untrained faces, and second to compare training effects between trained and untrained faces.

To assess maintenance of benefit in the five participants who did training first, we analyzed overall perceptual sensitivity, obtained by averaging over all six tests, and performed a *t* test between the results immediately after training with those after another 3 months doing the control task.

Secondary Outcomes

For secondary endpoints, we examined the impact of training on the other tests of face perception, using similar percent change indices and using *t* tests to determine if any changes were significantly different from zero.

Impact of Subject Variables

Subject variables may impact the efficacy of training (Bate & Bennetts, 2014). First we examined if prosopagnosic severity had an impact by looking for correlations between

baseline performance on each of the secondary tests of face perception or recognition listed above and the overall training effect obtained by averaging the percent change indices of all twelve tests. Second, given speculation that better results may occur in younger adults or more recent lesions (Bate & Bennetts, 2014), we tested for correlations between the overall training effect and subject age or the time since onset. Third, because it has also been suggested that training should be directed at the primary deficit (Bate & Bennetts, 2014), we used a *t* test to compare the overall training effect in the four with lesions limited to anterior temporal cortex versus the six with involvement of occipitotemporal cortex. Lastly, because of concerns that training may be less effective in those with bilateral lesions (DeGutis, Chiu, et al., 2014), we performed a *t* test to compare the overall training effect between those with unilateral and those with bilateral lesions.

RESULTS

Primary Outcomes

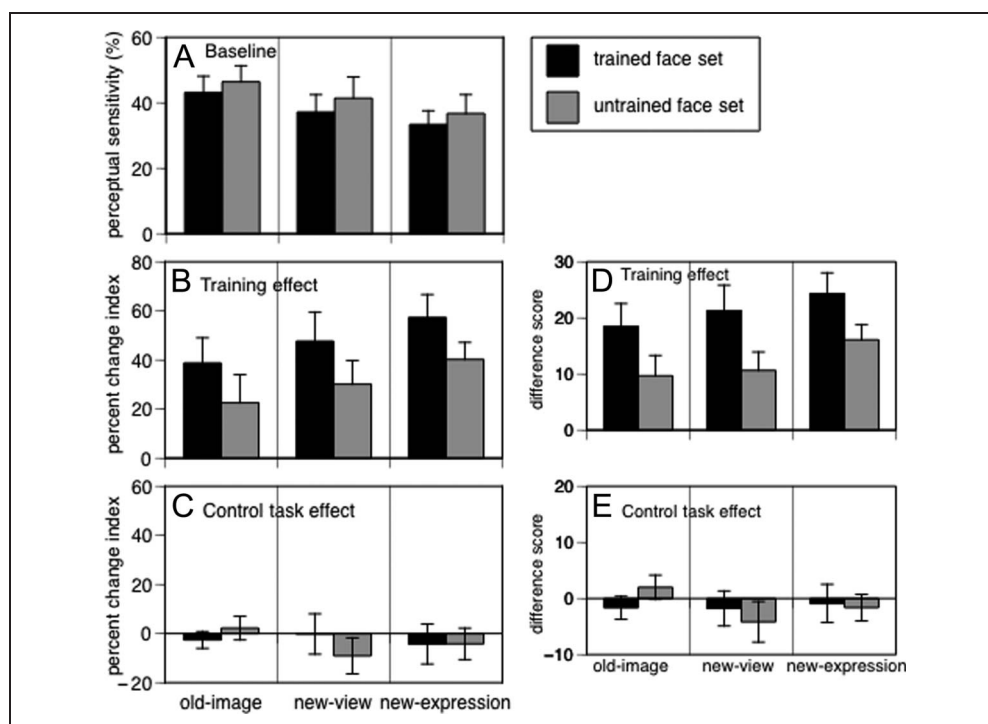
Before training, the baseline data showed no main effect of Face set ($F(1, 45) = 1.85, p = .18$); hence, these were equally difficult for the participants (Figure 5A). There was a main effect of Testing condition, though ($F(1, 45) = 4.53, p = .02$): Tukey's HSD test showed no difference between the old-image and new-view conditions, but the new-expression condition was more difficult than the old-image condition. Thus, even though all views and expres-

sions, old and new, were equally novel to the participants at the start, matching from the neutral to the surprised expression was more difficult. Hence, it is a good challenge for generalization.

The data for training and control effects on each participant's 12 online tests (6 for trained and 6 for untrained faces) are shown in Figure 6. The ANOVA of the percent change indices showed a large effect of Intervention ($F(1, 99) = 88.8, p < .0001$), due to a mean percent change improvement of 39% ($SD = 22.3$) after training, corresponding to a difference score of 17% in perceptual sensitivity ($SD = 6.8$), versus an effect of -2.9% ($SD = 13.2$) in the percent change index after the control task (Figure 5B–E). There was a main effect of Face set ($F(1, 99) = 4.11, p < .046$), due to larger improvements for trained than for untrained faces. There was a trend to an interaction between Intervention and Face set ($F(1, 99) = 2.99, p = .086$): Tukey's HSD test showed no difference in the control effect between the trained and untrained faces, whereas the training effect for trained faces was greater than that for untrained faces.

Analysis of the difference score revealed similar findings: an effect of Intervention ($F(1, 99) = 106, p < .0001$) and of Face set ($F(1, 99) = 6.63, p < .02$) but now with an interaction between Training and Face set ($F(1, 99) = 7.13, p < .009$), again with Tukey's HSD test showing a greater training effect for trained than untrained faces and no difference between these two face sets for the control effect.

Figure 5. (A) Baseline performance. Perceptual sensitivity is shown for the three test conditions for the trained and untrained faces. There is no difference between the trained and untrained faces or between the old-image and new-view conditions, but the new-expression condition is more difficult than the old-image condition. (B) Mean percent change with training for the three test conditions. Performance with new-view and new-expression are as good as with the old-image condition, indicating generalization. There is also a significant training effect for untrained faces, indicating transfer. (C) Mean percent change with the control task. This shows no effect on performance. Error bars show one standard error. (D) Training effects as in B, except now expressed as a difference score rather than percent change. (E) Control effects as in C, except now expressed as a difference score rather than percent change.



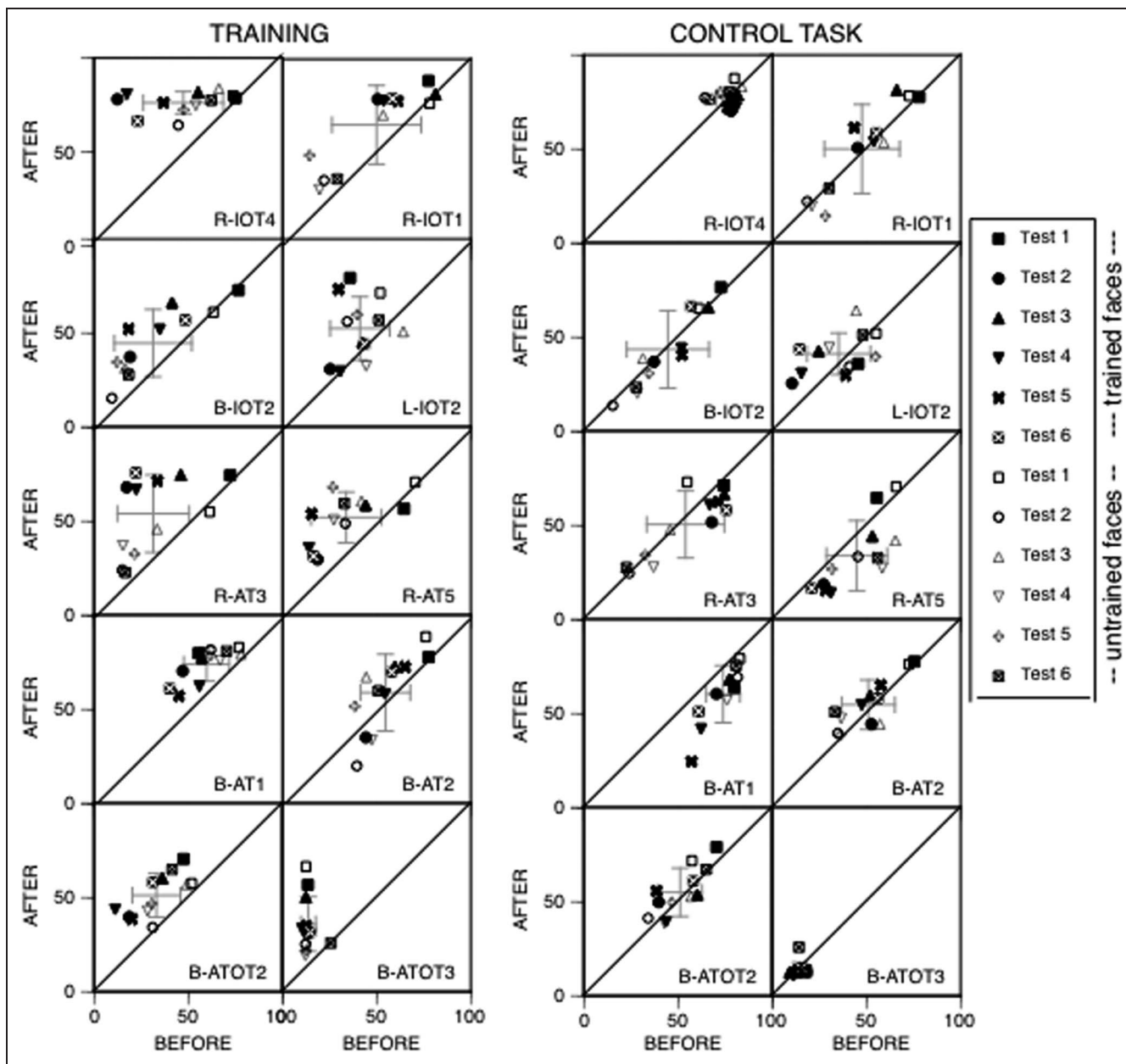


Figure 6. Perceptual sensitivity on the 12 online assessments, for each patient. The left set of graphs shows performance after training plotted against results before training. The right set of graphs shows performance after versus before the control task. Solid black symbols are for trained faces, and clear symbols for untrained faces. The average performance for all 12 tests is indicated by the large cross, whose arms show one standard deviation. Points above the diagonal lines correspond to better perceptual sensitivity after the intervention. In each set of graphs, those in the left column are for patients who did training first, whereas those in the right column are for those who did the control task first.

Generalization

The percent change from training was significantly different from zero not only for the old-image (38.8%, $SD = 32.4$, $t(9) = 3.78$, $p < .005$) but also for the new-view (47.7%, $SD = 35.5$, $t(9) = 4.02$, $p < .0031$) and new-expression (57.3%, $SD = 27.9$, $t(9) = 6.15$, $p < .0002$) testing conditions (Figure 5B). The results were similar for the absolute change in performance that was reflected in the difference score (Figure 5D, all $ps < .002$). Linear contrasts showed that the training effect on the percent change index was greater than the control effect not only

for the old-image condition ($F(1, 99) = 15.64$, $p < .0001$) but also for the new-view ($F(1, 99) = 31.12$, $p < .0001$) and new-expression ($F(1, 99) = 46.11$, $p < .0001$) conditions. The same was true for the difference score (all $ps < .0001$).

Transfer

The percent change due to training was significantly different from zero for both trained faces (47.4%, $t(9) = 5.42$, $p < .0004$) and untrained faces (30.1%, $t(9) = 4.99$,

$p < .0007$; Figure 5B). The corresponding effect on the difference score was a mean of 21.4% ($SD = 3.4$) increase in perceptual sensitivity for trained faces ($t(9) = 6.32, p < .0002$) and a mean of 12.1% ($SD = 1.6$) increase for untrained faces ($t(9) = 7.34, p < .0001$). Linear contrasts showed that the training effect was greater than the control effect for both trained faces ($F(1, 99) = 62.23, p < .0001$) and untrained faces ($F(1, 99) = 29.59, p < .0001$). Of note, linear contrasts also showed that the training effect was greater for trained faces than for untrained faces ($F(1, 99) = 7.06, p < .009$).

Maintenance

First, we show in the five participants who did the control task first that this did not alter perceptual sensitivity, which was 38.8% ($SD = 14.6$) at baseline and 38.7% ($SD = 16.1$) after the control task ($t(4) = 0.02, p = .99$). From this, we conclude that it is unlikely the control task altered performance during the posttraining period in the second group who did the training first.

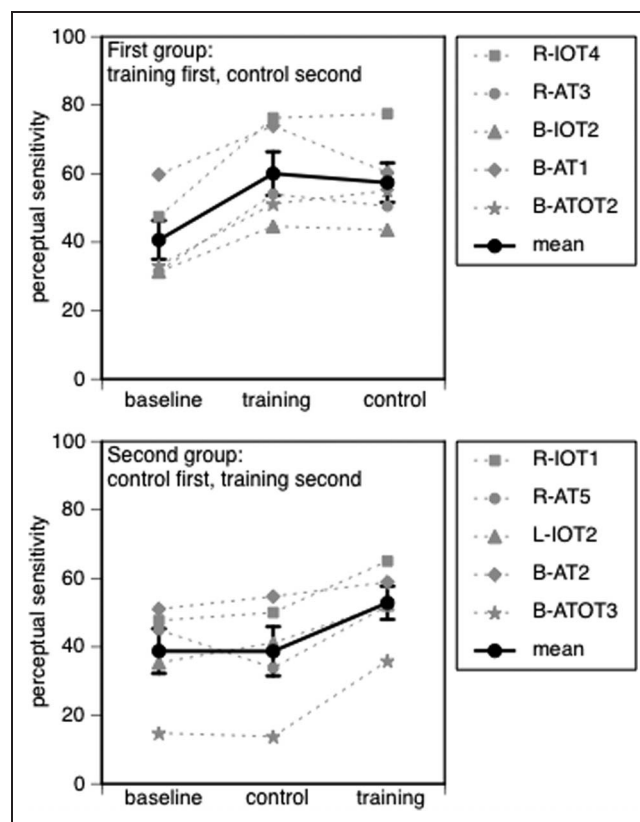


Figure 7. Maintenance. In the five participants who did the training task first (top graph), performance improves from baseline after training, and there is no significant decline after 3 months of the control task, without training. For comparison we also show data for the five participants who did the control task first (bottom graph). This shows no change in performance from baseline after the control task, but improvement after training. Dashed lines and gray symbols show scores of individual participants; black lines show mean for the group, with error bars indicating 1 SE.

In the five participants who did training before the control task, perceptual sensitivity increased with training from 40.7% ($SD = 10.1$) at baseline to 60.0% ($SD = 10.9$) after training ($t(4) = 6.74, p < .0002$). This improvement was still evident after 3 months of the control task (Figure 7), being 57.4% ($SD = 12.5$), which was not different from the score immediately after training ($t(4) = 0.88, p = .43$). This was true even for the untrained face set alone: perceptual sensitivity increased from a baseline of 43.3% ($SD = 14.7$) to 55.0% ($SD = 15.6, t(4) = 8.02, p < .001$) and did not show any decline after the 3-month control task (54.9%, $SD = 16.1, t(4) = 0.06, p = .96$).

Single-subject Analysis

Analyzing the percent change index, the effect of training was greater than the control effect for 7 of 10 participants, that is, all participants except R-IOT1, L-IOT2, and B-AT2. With the difference score as the outcome variable, the effect of training was greater than the control effect for eight of 10 participants, that is, all participants except L-IOT2 and B-AT2.

Secondary Outcomes

Training did not generate significant effects on other face perception tests. On the Cambridge Face Memory Test, the mean improvement with training was 10.2% ($SD = 18.9$), compared with no improvement with the control task (mean = -4.0% , $SD = 20.3$), but this difference did not reach significance ($t(9) = 1.33, p = .22$). Likewise the gain from training for the overall score for the test of discrimination of features and spatial changes was 6.8% ($SD = 16.9$), compared with little change for the control task (mean = 0.0% , $SD = 24.7$), which also did not reach significance ($t(9) = 1.20, p = .26$).

Impact of Subject Variables

There was a correlation between the overall training effect and baseline performance on both the Cambridge Face Perception Test ($r = .63, F(1, 9) = 5.78, p < .040$) and a test of perceptual discrimination of interocular distance (Malcolm et al., 2005; $r = .62, F(1, 9) = 5.52, p < .044$). In both cases, participants with more perceptual difficulty at baseline gained the most from training. In contrast, baseline performance on the Warrington Recognition Memory Test or the Cambridge Face Memory Test did not correlate with the overall training effect.

There was no correlation with subject age or the duration of prosopagnosia. The overall training effect did not differ between those with lesions limited to the anterior temporal lobe (30.9%, $SD = 20.4$) and those whose lesions included occipitotemporal cortex (43.8%, $SD = 23.8$). The overall training effect also did not differ between those with unilateral (41.9%, $SD = 11.4$) and those with bilateral lesions (36.5%, $SD = 28.4$).

Subjective Reports

R-AT3 (overall training gain 53%) noted a general improvement in his ability to recognize colleagues and clients and felt more confident in this ability. He recalled three notable experiences. Usually he had difficulty recognizing individuals out of context, but during training he recognized a colleague in the supermarket. Two weeks after training, he met a man who looked familiar, who turned out to be the brother of a friend of his, whom he had never met. He also recognized his nephew when he went to pick him up.

R-AT5 (gain 42%) claimed to attend to the eyebrows and eyes during the training task and felt that in daily life this shifted her focus from the mouth and chin to the overall shape and outline of faces, but she did not note any benefit in face recognition.

R-IOT1 (gain 26%) felt more confident when attempting to identify a face and as a result enquired to his partner on fewer occasions who is who. However, he did not note any obvious changes in his ability to recognize people or the cues he used.

R-IOT4 (gain 47%) felt that the training made him aware that the distances between features are important cues and felt more frequent and enhanced feelings of familiarity with faces. He was coping better with face recognition and attributed this to changes in how he regarded facial features. He noted no change in his ability to name faces, though.

L-IOT2 (gain 24%) found during training that his search for identity cues shifted from people's clothes to parts of faces and then whole faces. He began to look at eyes and eyebrows more, whereas before he had focused on the nose and mouth. He did not note any improvement in face recognition, though. In a conversation about 3 months later, he mentioned that he was reverting to looking at hair and clothes.

B-IOT2 (gain 35%) noted that he was looking at the eyes more to identify faces and stated, "It feels like faces are different." Although he reported, "It feels more like I'm closer to recognizing them," he did not feel that the training improved his recognition of the faces of his friends and family. However, while watching his favorite sports team, "This year I seem to be able to pick out some, not all, of the players a lot better. Maybe their faces are slightly easier for me to pick out.... It's not perfect by any stretch but it does seem to be a little better than before the training... I think I have improved ever so slightly there. I'm not really seeing any changes in other situations... I seem to be recognizing the entire face. It's not the mouth or hair... it's more like I get the sense their face is more recognizable... I'm positive that if those faces were in an unfamiliar setting I wouldn't recognize them at all."

B-ATOT2 (gain 42%) reported no changes in recognition accuracy but felt that she was learning to recognize faces by looking more at features than hairstyles. She was

paying more attention to faces and becoming more confident in making judgments about the identity of people.

B-ATOT3 (gain 89%) believed he had improved and that he "finds it easier to recognize people sometimes" and is "more aware of people's eyes now." His mother commented that his "social skills and socialization have improved immensely since beginning the study." On picking him up from school, she noted that whereas he previously did not bother trying to find her in the crowd of parents, he now "looks closely at my face to make sure it is me."

Neither B-AT1 (gain 21%) nor B-AT2 (gain 7%) noted changes in daily face recognition.

DISCUSSION

A perceptual learning approach aimed at discriminating whole-face differences over a variety of views and expressions resulted in improved discrimination for trained faces that generalized to new views and expressions of those faces. These effects persisted for at least 3 months and were not generated by a control task. In addition, there was transfer to untrained faces. Although effects on standard tests of face processing were minimal, some but not all patients perceived benefits in daily life. Improvement occurred both in those with an associative subtype from anterior temporal lesions and those with an apperceptive subtype from occipitotemporal lesions and both in those with unilateral and those with bilateral lesions.

Control tasks are important to show that learning effects are due to the training and not to nonspecific factors that occur with any intervention. A subject-blinded placebo control as done in an oxytocin trial (Bate et al., 2014) is ideal but not usually possible for rehabilitative studies, where it is difficult to hide from a participant that they are undergoing training. We minimized experimenter bias at least by ensuring that those administering assessments were blinded. Although several cases did not report a control, others have provided some measures. Repeated baseline tests that establish stability and reproducibility of pretraining performance could also be regarded as a control measure to show the effect of no training (Dalrymple, Corrow, Yonas, & Duchaine, 2012; Schmalzl, Palermo, Green, Brunsdon, & Coltheart, 2008; Brunsdon, Coltheart, Nickels, & Joy, 2006). An equivalent strategy is a waiting period without intervention (DeGutis, Cohan, et al., 2014), but this and repeated baselines may not control for general factors such as motivation or enhanced attention and exposure to faces. When transfer of effects is not an issue, another control is learning of a second set of faces without the specific instructions of the training set (Powell et al., 2008; Francis et al., 2002; De Haan et al., 1991). In our study, we provided a television drama control that involved tracking of characters over episodes and regular interactions with the examiner that probed their attention to the plot and found no benefit from this activity on our face assessments.

Whether effects generalize to new views of trained faces is not only important for ecological validity but can inform us about the type of processing at which learning is occurring. Generalization suggests that learning is operating on 3-D expression-invariant representations, whereas lack of generalization points to effects on lower-level image processing. For mnemonic strategies in two patients with acquired prosopagnosia, the enhancement of familiarity by semantic associations in a single block of training did not generalize to new views (Polster & Rapcsak, 1996), but the enhancement of face identification by 2 weeks of semantic training did (Francis et al., 2002). In developmental prosopagnosia, the compensatory strategy of explicitly attending to features showed delayed generalization to new views in K (Schmalzl et al., 2008) and AL (Brunsdon et al., 2006). Among remedial approaches, repeated training of TM to recognize his mother did not transfer to new views (Dalrymple et al., 2012), and holistic training with faces in frontal view did not improve the performance of 24 developmental prosopagnosics on perceptual tests with faces in other views (DeGutis, Cohan, et al., 2014). Our perceptual learning approach in acquired prosopagnosia did show robust generalization of effects to both new views and new expressions.

The transfer of training benefits to new faces is important. Transfer is evidence of acquisition of a new perceptual skill or relearning of an old one that can be applied to new stimuli. Absence of transfer is more compatible with overlearning of a stimulus set with existing skills (although some skill development might be evident as faster learning of a second stimulus set). Although overlearning can be useful if applied to a set of important, frequently encountered faces, skill development is the outcome with broader utility for daily life.

Mnemonic approaches that use specific semantic information are aimed at enhancing recall or identification of a specific face, not of all faces. Hence, transfer is not relevant. On the other hand, transfer is a valid concern for perceptual approaches, whether a feature-based compensatory strategy or remedial perceptual learning of faces. In developmental prosopagnosia, explicit attention to features did not translate to improved recognition of a second set of faces in AL (Brunsdon et al., 2006). In some but not all of 24 participants with developmental prosopagnosia, perceptual learning showed transfer in that it improved performance on other tests of face processing (DeGutis, Cohan, et al., 2014; DeGutis et al., 2007). This did not occur with the same training method in one participant with acquired prosopagnosia (DeGutis et al., 2013). Perceptual learning improved performance on the Cambridge Face Perception Test but not the Cambridge Face Memory Test in EM, who had acquired prosopagnosia (Bate et al., 2015). In our study, we found strong evidence of transfer to new faces. Hence, perceptual learning of faces in acquired prosopagnosia does result in acquisition of new skills, though the larger effect

with the trained face set may reflect some overlearning of a stimulus set as well. There was minimal impact on other face tests, however. This might reflect the additional memory processes involved in tests of short-term familiarity, which our perceptual training program did not target, the use of purposefully degraded images on some of these tests, the modest number of participants we trained, and the possibility of deficits in other functions related to person recognition in some of our participants, such as those with bilateral anterior temporal lesions (Liu et al., 2016).

Benefit in daily life would be further evidence of transfer, as well as showing ecological validity of the results. Assessing real-life benefit is difficult, however. Anecdotal reports include better use of features to recognize people in subject Ch. (Beyn & Knyazeva, 1962) and the increased confidence of PS in looking after her schoolchildren (Mayer & Rossion, 2007). EM also felt more confidence, though she also admitted no improvement in daily face recognition (Bate et al., 2015). Our participants varied in their impression of daily experience after treatment: Whereas some reported positive real-life experiences, a few noted no impact, particularly the two with bilateral anterior temporal lesions, who also had the smallest overall training effects.

The maintenance of benefit beyond the period of training is a desirable outcome. It is not mandatory, however: A benefit that requires reinforcement by occasional practice would still be an advance. Assessment of maintenance has only been done occasionally and at widely varying intervals. The enhancing effect of semantic information on face familiarity in RJ was retained 20 min after a single training session in one study (Polster & Rapcsak, 1996) and on face identification in NE 1 week after a 2-week program (Francis et al., 2002). However, the modest effects of semantic context in prompting recognition in PH were not evident 2 months later (De Haan et al., 1991). For feature-based compensatory approaches, improved face discrimination persisted 1 month (Schmalzl et al., 2008) and possibly 3 years later in K (Wilson, Palermo, Schmalzl, & Brock, 2010) and after 3 months in AL (Brunsdon et al., 2006). For perceptual training, EM's slight benefit in correctly rejecting unfamiliar faces was maintained 1 month after training (Bate et al., 2015), whereas MZ showed some savings in reaction time but not in accuracy after 3 months (DeGutis et al., 2007). Our study shows that perceptual gains in the accuracy of face discrimination from 11 weeks of training persist after 3 months, even when assessed on the untrained face set, over a period when participants were performing the control task. A direct contribution to performance from the control task is unlikely given that it did not alter perceptual sensitivity in the participants who did the control task first. However, it is possible that the control task may have had a secondary role in assisting the maintenance of the training effect, if continued engagement with faces is an important factor. Regardless, the results clearly

show that training benefits can endure for at least several months.

One therapeutic concern is whether efficacy depends partly on subject-related factors (Bate & Bennetts, 2014; DeGutis, Chiu, et al., 2014). It has been speculated that young patients may show a U-shaped function, with the best rehabilitative potential in early childhood (Bate & Bennetts, 2014). It was also inferred from trauma studies (Katz & Alexander, 1994) that there may be even less potential in the elderly. Another potentially important temporal factor in acquired cases is the duration since onset. Following an injury, there may be a window of opportunity when cerebral plasticity is greatest (Dobrossy & Dunnett, 2005). With a few exceptions (Beyn & Knyazeva, 1962), most rehabilitative trials in patients with acquired prosopagnosia have started years after onset, and our study is no exception. Thus, although we did not find an impact of age or duration of prosopagnosia, we cannot exclude the possibility of greater benefits with application of the program much earlier after onset in younger participants.

The structural extent of a lesion may have an effect. It is unclear whether improvement of prosopagnosia would be mediated through synaptic reorganization within a region, as occurs during brain development (de Schonen, Mancini, Camps, Maes, & Laurent, 2005), or through anatomic reorganization involving other cortical regions, and if so, whether these would be general object processing resources or other components of the face-processing network, in particular those in the left hemisphere. The latter point is reflected in concerns that patients with bilateral lesions may have less rehabilitative potential (Bate & Bennetts, 2014; DeGutis, Chiu, et al., 2014) and the observation that partial recovery in the few studies of natural history seem to be mainly in those with unilateral lesions. In the prior training reports, five patients had bilateral occipitotemporal lesions (Bate et al., 2015; Powell et al., 2008; Mayer & Rossion, 2007; De Haan et al., 1991; Beyn & Knyazeva, 1962), three had right occipitotemporal lesions (DeGutis et al., 2013; Behrmann et al., 2005; Polster & Rappaport, 1996), and one had a right temporal lesion (Francis et al., 2002); reported benefits were not limited to those with unilateral lesions. Likewise, in our study we observed benefit with bilateral or unilateral right lesions.

It has also been suggested that the type of training should be targeted to the functional deficit (Bate & Bennetts, 2014). This guided approach is best exemplified by a study of a patient with preserved face perception but loss of both structural knowledge about faces and semantic information about people, in whom benefit was obtained by a mnemonic approach that incorporated both faces and semantic data (Francis et al., 2002). In the other training studies of acquired prosopagnosia, most patients had evidence of impaired perceptual processing of faces (Table 1). This is also true of some of the developmental prosopagnosics trained such as AL (Brunsdon et al., 2006), MZ (DeGutis et al., 2007), and K (Schmalzl et al., 2008). In the group studies, poor performance on

the Cambridge Face Perception Test was seen in only 1 of 10 participants in one study (Bate et al., 2014) but in 14 of 24 in the other (DeGutis, Cohan, et al., 2014). However, functional data have had little influence on whether mnemonic or perceptual training was used in any given study. In our trial, perceptual learning yielded similar benefits in those with occipitotemporal lesions and those with anterior temporal lesions. Our prior studies, including of this cohort (Liu et al., 2016), have shown that apperceptive deficits are the core impairment after occipitotemporal lesions, as shown on tests of perception of facial structure, whereas anterior temporal lesions cause an associative/ amnesic variant, with relatively intact perception of faces (Davies-Thompson et al., 2014; Barton, 2008). The finding that both groups show benefit from training may reflect the fact that the associative/apperceptive dichotomy is relative rather than absolute, as some perceptual impairment can also be shown in participants with anterior temporal lesions (Busigny et al., 2014; Barton, Zhao, & Keenan, 2003). Nevertheless, our correlation analysis did show that benefit was greater in those with more severe impairments in face perception, which lends some support to the proposal that perceptual training leads to greater gains in those with perceptual deficits (Bate & Bennetts, 2014).

What specific aspect or type of perceptual processing of faces improved with our training is not something that we studied. Others have suggested that similar training can enhance holistic processing in some but not all participants, as indexed by the inversion effect or the part-whole effect (Bate et al., 2015; DeGutis, Cohan, et al., 2014). To encourage whole-face processing, we did not give instructions to attend to any face part, and as stated in our methods, some aspects of our design were aimed at preventing a laborious serial feature matching strategy. Nevertheless, some participants reported that after training they found themselves paying more attention to the eyes. A study of this cohort has shown relatively greater impairment in processing the shape and spatial relations of the eyes, especially under attentionally demanding conditions, particularly in those with occipitotemporal lesions (Pancaroglu et al., 2016). Hence, it may be that, in some, training improved a relative deficit in ocular processing, which has been described in other prosopagnosic participants as well (Busigny, Joubert, Felician, Ceccaldi, & Rossion, 2010; Caldara et al., 2005; Barton et al., 2002). This may be important given that the eyes contribute the most diagnostic information for face identification (Malcolm, Lanyon, Fugard, & Barton, 2008; Schyns, Bonnar, & Gosselin, 2002).

Functional characterization is important for another reason, clarifying the specificity of the diagnosis. In some reports, face recognition impairment may have been part of a broader problem with general visual agnosia (Brunsdon et al., 2006), and it may be that deficits at a more basic level of visual analysis account for limited training efficacy. Likewise, participant K may have had an autistic spectrum disorder (Wilson et al., 2010), and whether K's results

should be extrapolated to developmental prosopagnosia can be debated.

In summary, our results suggest that perceptual learning in patients with acquired prosopagnosia can result in enhanced perceptual discrimination of faces that persists for several months. Because the effects generalize to different views of the trained faces, this is likely operating at the level of 3-D expression-invariant representations. Because there is transfer to untrained faces, this suggests acquisition of new skills rather than just overlearning of a training stimulus set. Nevertheless, the larger learning effect with trained faces suggests some element of overlearning as well. Although training did not lead to better performance on some other face tests, at least some patients reported benefits in their daily life. Although effects were larger for those with greater face perception deficits, they were similar for apperceptive and associative/amnesic subtypes, indicating that even those whose chief deficit was access to facial memories could benefit from perceptual training. Although these are encouraging results, it is also clear that this training approach is not a panacea for prosopagnosia. Further studies are warranted: In particular, approaches that couple training with the use of agents that promote plasticity and learning (Rokem et al., 2012; Dinse, Ragert, Pleger, Schwenkreis, & Tegenthoff, 2003) may be valuable.

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Reprint requests should be sent to Jason J. S. Barton, Neuro-ophthalmology Section K, VGH Eye Care Centre, 2550 Willow Street, Vancouver, BC, Canada, V5Z 3N9, or via e-mail: jasonbarton@shaw.ca.

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