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Face Memory Deficits in Patients Deprived of Early Visual Input by Bilateral Congenital Cataracts

ABSTRACT: *Patients treated for bilateral congenital cataract are later impaired on several hallmarks of adults' expertise with upright faces but report no problem with remembering faces. Here, we provide the first formal data on their face memory. We compared 12 adults with a history of visual deprivation from bilateral congenital cataracts to 24 age-matched controls with normal vision on their ability to recognize famous and recently learned faces, and on their subjective impression of their face memory. Bilateral congenital cataract patients demonstrated a prosopagnosic-like deficit, being slower and less accurate in recognizing both famous faces and recently learned faces, despite not differing on most questions about their impression of their face memory. Patients' results on three perceptual tasks (the composite face effect, the Benton test of recognizing faces through a change in point of view, and the Jane test of sensitivity to feature spacing) were also not correlated with their face memory deficits. These results suggest that early visual input is necessary not only for perceptual expertise in differentiating among unfamiliar upright faces, but also for normal accuracy in remembering the identity of individual faces.* *© 2012 Wiley Periodicals, Inc.* Dev Psychobiol

Keywords: *cataract; prosopagnosia; faces; visual deprivation; face memory*

INTRODUCTION

Human newborns are drawn towards face-like patterns (e.g., Goren, Sarty, & Wu, 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991; Johnson & Morton, 1991; Valenza, Simion, Macchi Cassia, & Umiltà, 1996). Yet their poor visual acuity and contrast sensitivity restrict the information they can extract from faces (Banks & Bennett, 1991; de Heering et al., 2008) and they lack most specialized mechanisms adults use to process faces differently from objects (Turati, Bulf, & Simion, 2008; Turati, Macchi Cassia, Simion, & Leo, 2006). Nonetheless, early visual inputs play a crucial role in the development of adult-like expertise in face processing, as indicated by the deficits observed in adults who missed early visual input because dense and central cataracts in both eyes blocked patterned visual input until the cataracts were removed surgically and the eyes fitted with compensatory contact lenses. Such later deficits have been observed even in patients treated so early that they missed only the first 1 or 2 months of visual input (reviewed in Maurer, Mondloch, & Lewis, 2007).

Despite early visual deprivation, when tested later in life, cataract-reversal patients are able to categorize a stimulus as a face, with the same accuracy and speed as individuals with normal vision (Mondloch, Le Grand, & Maurer, 2003). Face detection can, therefore, develop normally even in the absence of early visual

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input. Such patients are also as good as controls at matching faces based on the direction of eye gaze, facial expression, or sound being mouthed, at least for the gross types of discrimination that were tested, which likely require only featural processing (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002). They are also normal at matching individual faces based on the shape of their internal features or of their external contour (Le Grand, Mondloch, Maurer, & Brent, 2001; Mondloch et al., 2003), even when the feature differences include ones that are hard to detect for adults with normal vision (Mondloch, Robbins, & Maurer, 2010). These capabilities are normal later in life even when the deprivation lasted throughout the first 6 months of life. In contrast, cataract-reversal patients show a deficit compared to controls when they are asked to recognize the identity of individual faces across changes in point of view (Geldart et al., 2002). This deficit may arise from their difficulty in differentiating between faces based on the spacing between their internal features (Le Grand et al., 2001), a deficit that is restricted to human upright faces and does not extend to monkey faces or houses (Robbins, Nishimura, Mondloch, Lewis, & Maurer, 2010). Alternatively, or in addition, the deficit in recognizing the identity of a face in a novel viewpoint may arise from their failure to process faces holistically (Le Grand, Mondloch, Maurer, & Brent, 2004), as evidenced by their failure to show a composite face effect (Young, Hellawell, & Hay, 1987), which is a signature of normal holistic processing (Maurer, Le Grand, & Mondloch, 2002).

Interestingly, patients who acquired prosopagnosia after a brain lesion also have no composite face effect and abnormally poor sensitivity to feature spacing (Barton, Press, Keenan, & O'Connor, 2002; Barton & Cherkasova, 2005; Busigny, Joubert, Felicien, Ceccaldi, & Rossion, 2010; Joubert et al., 2003; Levine & Calvanio, 1989; Ramon, Busigny, & Rossion, 2010; Ramon & Rossion, 2009; Rossion, Kaiser, Bub, & Tanaka, 2009; Sergent & Villemure, 1989). Acquired prosopagnosia is typically defined as a selective inability to learn novel facial identities and to recognize the identity of familiar faces (e.g., Bodamer, 1947; Charcot, 1883; Quaglino & Borelli, 1867; Wigan, 1844). In many cases, such patients are also normal at face detection (Busigny et al., 2010).

Unlike patients with acquired prosopagnosia, patients treated for bilateral cataracts have told us that they have no difficulty recognizing the faces of their family and friends. If these self-reports are correct, then they imply that, intact holistic processing, sensitivity to feature spacing and matching identity through different viewpoints are not necessary for normal ability to remember the identity of learned faces. Yet, the face memory of cataract-reversal patients has never been tested formally. This is the purpose of the present study. We assessed face memory by measuring the ability to recognize famous faces (Famous Faces Task) and recently learned faces (Cambridge Face Memory Test). We also evaluated patients' subjective impression of their face memory with a questionnaire we constructed specifically for this study (Prosopagnosic Questionnaire). Finally, we assessed the relationship between any deficit in face memory and patients' perceptual deficits by measuring their sensitivity to the composite illusion that indexes holistic face processing (Composite Face Task; see Le Grand et al., 2004), their sensitivity to spacing between facial features in human and monkey faces (Monkey Jane Task; see Le Grand et al., 2001; Robbins et al., 2010), and their ability to match simultaneously presented faces with different points of view (Benton Face Recognition Test; de Heering, Rossion, & Maurer, 2011). The results from cataract-reversal patients were compared to those of 24 age-matched controls with normal vision. Based on previous findings, we predicted that patients would be less sensitive than controls to the composite illusion (Le Grand et al., 2004), to feature spacing in upright human faces (Le Grand et al., 2001; Robbins et al., 2010) and to the identity of an unfamiliar face presented from different viewpoints (Geldart et al., 2002). Because these perceptual deficits match those reported in acquired prosopagnosia, we also suspected that patients would be significantly impaired in the tests of face memory (Famous Faces Task, Cambridge Face Memory test) despite the absence of complaints about their face recognition abilities (Prosopagnosic Questionnaire). Finally, we hypothesized that the magnitude of patients' deficit on the perceptual tasks would correlate significantly with their ability to recognize famous faces (Famous Faces Task) and recently learned faces (Cambridge Face Memory Test) because we expected the perceptual deficits to compromise the fidelity of encoding.

METHODS

Participants

Visually Deprived Patients. The patient group consisted of 12 patients treated for bilateral congenital cataracts, aged 16–30 years at the time of testing (6 males; mean age = 21 years; *SD* = 5). They were included in the sample only if they had been diagnosed with bilateral dense and central cataracts on the first eye exam before 6 months of age and if there was evidence that the cataracts had blocked all patterned visual input to the retina. We assumed that these patients had been visually deprived from birth because it would be unusual to have dense cataracts develop rapidly between birth and 6 months of age. The included patients also had no history of neurological or retinal disorders. Patients' period of deprivation, from birth until the age of first optical correction after surgery, ranged from 9 to 238 days (Tab. 1). Thus, they had years of visual input after treatment with which to tune the face recognition system. Their letter visual acuity in the better eye on the day of the test ranged from 20/25 to 20/125 (Tab. 1).

Visually Normal Controls. Twenty-four (19 females; mean age: 20 years; $SD = 1$; range: 18–21 years) undergraduate students at McMaster University (Canada) participated for course credit. We had twice as many controls as patients in order to obtain the best approximation of normal performance on the battery of tests and because the structure of the analyses was robust to unequal samples. The mean age of the control group was not significantly different from the mean age of the patient group ($t(34) = 1.124$, $p = .269$). All controls passed a screening exam for normal vision and had no history of eye or neurological problems. All were able to read the 20/20 line on the eye chart with each eye either on the first attempt ($N = 20$) or after being given an optical correction of $-.5$ ($N = 4$). A deterioration in acuity when a +3D lens was placed over each eye ruled out farsightedness of 3D or more.

General Procedure. The Research Ethics Boards of McMaster University and of The Hospital for Sick Children (Canada) approved the experimental protocol. Before testing, and after explaining the experimental procedures, we obtained written consent from participants or from their legal guardian if they were under 18 years of age.

For practical reasons, the tasks were administered in three pairings, with the order of the pairings and the tasks within the pairings counterbalanced across participants, in each group. The first pairing consisted of the paper and pencil tests, namely the Famous Faces Task and the Prosopagnosic Questionnaire. The second pairing consisted of the Cambridge Face Memory Test and the Benton Face Recognition Test, which were run with Superlab 4.0.7b on a Mini Mac controlled by an OSX 10.4.2 system. The third pairing consisted of the Composite Face Task and the Monkey Jane Task, which were controlled by Superlab 1.77 running on a PowerMac G4 Cube controlled by an OS.9.2.1 system. For all but the Famous Faces Task and the Questionnaire, participants sat in a dimly lit room 100 cm away from a Dell Trinitron computer monitor that measured 50.5 cm diagonally (i.e., 28.8° of visual angle). All tests were binocular.

The Famous Faces Task

Participants were told that they would be presented with 60 faces, some of which are famous. The famous and non-famous faces had been selected from the Internet and had been screened for being of good quality and easily recognized by 13- to 15-year-old adolescents in 2008, that is 3 years before the current data were collected, and hence likely to be familiar to the age cohort we tested. Participants were asked to write the name of any person they recognized as being famous in the first column of the response sheet. If they recognized the person as famous but could not recall the name, they were instructed to give as much specific information as possible about the person in the second column of the response sheet (e.g., name of the movie the actress acted in). If they could not remember anything about the person or thought the person was not famous, they were asked to check the "don't know" (third) column of the response sheet. Half of the 60 faces were of famous people; half were not. After this part of the task was completed, we assessed whether each

Table 1. Details of the 12 Patients Treated for Bilateral Congenital Cataracts

Patients			Linear Letter Acuity		Duration of Deprivation
Gender	Age at Test	Secondary Visual Problems	Left	Right	Contacts
M1	29	Glaucoma	20/80	20/32	187
M2	19	Glaucoma	20/200	20/32	238
F1	17	Glaucoma	20/80	20/40	81
F2	17	Nystagmus, surgery for LET OU	20/32	20/80	92
M3	18	Glaucoma	20/25	20/32	48
F3	30	Glaucoma	20/100	20/50	129
F4	18	Glaucoma	0/8	CF	143
F5	19	Glaucoma, nystagmus	20/125	20/200	134
M4	16	Glaucoma	20/50	CF	9
M5	25	Glaucoma, nystagmus	20/125	20/100	142
F6	20	Glaucoma, nystagmus	20/32	20/80	152
M6	20	Glaucoma	20/125	20/200	139

Secondary visual problems are ones that arose as a result of the initial deprivation. OU refers to both eyes. Glaucoma was in every case being controlled successfully by drugs and there had been no damage to the retina. The values reported for the Letter Acuity refer to the best-corrected letter acuity on the day of testing. CF stands for counting fingers. The duration of deprivation is the period in days from birth until the fitting of a compensatory contact lens or glasses after surgery, which occurred on the same day for both eyes.

participant had been exposed previously to the selected famous faces and hence could be expected to remember them. Specifically, participants were given a list of 45 names (30 names of famous people they were exposed to during the first part of the test among 15 non-famous names). They were instructed to add a "1" next to the name if they thought they would be able to recognize this person based on his/her face and a "0" if not. For the corrected analysis, faces in the first part of the test that received a score of 0 on the second-half were not included.

The Cambridge Face Memory Test

The Cambridge Face Memory Test has been described in detail (e.g., Duchaine & Nakayama, 2006). Briefly, the Cambridge Face Memory test consists of three phases (introduction, no noise condition, noise condition), each composed of a learning and of a testing phase. Participants see unfamiliar faces that they are then asked to recognize among distractors. They indicate their response by pressing as accurately and as fast as possible the number on the keyboard corresponding to the studied face. In the introduction (18 trials), there are six target faces to be memorized. Each identity is first presented sequentially on the screen, starting with its left 1/3 profile, then its frontal view and finally its right 1/3 profile. Then, during the 18 test trials, the exact match to each target face has to be recognized among two distracters. In the no noise condition (30 trials), the studied faces are the same six full-frontal identities, presented first all at once for 20 s for review. As in the introduction, they then have to be recognized within triplets of faces but now with variations in point of view between the target and its match. Finally, in the noise condition (24 trials), all face images are embedded in noise with a change in point of view between the targets and the matches.

Prosopagnosic Questionnaire

This test was created specifically for the purpose of this experiment. The experimenter read 10 questions to the participants about their face memory (see Tab. 2) and asked them to rate their own performance on Likert scales from 1 to 7, with 1 indicating "not at all" and 7 indicating "a lot."

The Composite Face Task

We used the original type of composite task (Hole, 1994; Young et al., 1987) rather than the so-called full design of Richler and colleagues (e.g., Richler, Cheung, & Gauthier, 2011) because the original version taps the perceptual level of processing more directly by instructing participants to respond to the similarity of the top halves throughout rather than asking them to hold the first stimulus in memory until told at the time of the second stimulus whether to respond to the similarity of the top or bottom halves. Another reason for choosing the original design is the recent evidence that the composite effect is revealed in event-related potentials at an early stage of perception rather than a later decisional stage (Kuefner, Jacques, Prieto, & Rossion, 2010).

The stimuli and procedure were identical to those used by Le Grand et al. (2004). Briefly, participants saw pairs of faces, the top and bottom of which were either aligned with each other or laterally offset by half a face width. They were asked to make same/different judgments about the top halves of each face pair by pressing as accurately and quickly as possible the "s" or the "d" key of the keyboard if the response was same or different, respectively. The top half of the face was in the same location on all trials. In the aligned condition, it was perfectly fused with the bottom half of a different face and formed an image 6° (wide) $\times$ 8° (tall) from the viewing distance of 100 cm. In the misaligned condition, the bottom half was shifted horizontally to the right by half a face width and formed an image of 9° (wide) $\times$ 8° (tall) from the viewing distance of 100 cm. The same faces were used in the two conditions.

Each trial started with a fixation cross. When the participant pressed the spacebar, a composite face appeared for 200 ms, and following a 300 ms inter-stimulus interval, a second composite face appeared for 200 ms. The aligned and misaligned conditions were blocked and participants always performed the misaligned condition first. Within each block, half of the faces shared identical top halves (same trials; $n = 48$), and half had different top halves (different trials; $n = 48$). The bottom halves were always different. Same and different trials were intermixed within each block. Prior to each block, participants received four practice trials.

Table 2. Questions Included in the Prosopagnosic Questionnaire

Q.1	Are you easily able to recognize and identify faces of people you already met?
Q.2	In general, do you have the impression of being less accurate than other people in recognizing familiar faces?
Q.3	Do you have to use particular strategies to recognize faces?
Q.4	Do you often mix up people's faces?
Q.5	Do you have trouble recognizing faces?
Q.6	Do you think you are very good at recognizing faces?
Q.7	Do you find it sometimes hard recognize certain members of your family?
Q.8	Do you tend to mix up people when you are watching a movie?
Q.9	Do people tell you that you are not recognizing faces properly?
Q.10	Do you ever feel familiar with a person without being able to tell who it is?

Participants judged each of them on a Likert scale ranging from 1 to 7, with 1 indicating "not at all" and 7 indicating "a lot."

The Benton Facial Recognition Test

The stimuli and procedure were based on the original Benton Face Recognition Test (Benton, Sivan, Hamsher, Vereny, & Spreen, 1983) and identical to the computer adaptation used in de Heering et al. (2011). Briefly, stimuli were grayscale male or female Caucasian faces posing with neutral expressions. On every trial, the target stimulus was a full frontal face positioned in the middle of the upper part of the screen. The probes were organized in two rows of three faces below the target face. In Part 1 (six trials), the targets and probes shared the same lighting and the same point of view. In Part 2 (16 trials), the probes were taken with different lighting and unlike the targets, presented in 3/4 view. The target faces were slightly larger ($5^\circ \times 8^\circ$ from a distance of 100 cm) than the probe faces ($7^\circ \times 8^\circ$ from a distance of 100 cm) to encourage processing of facial identity rather than stimulus matching.

The participant's task was to find as accurately and quickly as possible the probe face that matched the target face (Part 1) or the three different probe faces that matched the target face (Part 2), by clicking on the matching face(s) on the screen using the mouse. The trials were separated from each other by blank intervals of 500 ms. The position of the correct choice was randomly distributed across the six positions and was the same for all subjects. Prior to Part 1 and again prior to Part 2, participants were given an example showing the structure of the task.

The Monkey Jane Task

The stimuli and procedure were identical to those used in Robbins et al. (2010). Briefly, we used upright and inverted faces of humans and monkeys in which the spacing of the internal features had been manipulated in the same way by moving their eyes up/down and in/out, and by moving their mouth up and down to create five different arrangements. Importantly, in the human and monkey face sets, the eyes and mouth of the five arrangements were manipulated in the same way. All faces were $6^\circ \times 9^\circ$ of visual angle from a distance of 100 cm. The type of face was blocked, with upright human faces presented first and upright monkey faces presented second, followed by inverted faces in the same species order. There were 30 faces in each block. At the end of each block, participants also performed the same task with unmanipulated human and monkey faces (32 trials) in order to gauge whether they were paying attention at the end of the task and whether patients were as good as controls with normal vision in differentiating faces in which both features and spacing vary naturally.

Before each block, participants were shown all five spacing arrangements to make them aware of the range of similarity among the faces. They also completed four practice trials before each block. Each trial started with a fixation cross. After the participant pressed the spacebar, a monkey or human face appeared in the centre of the screen for 200 ms, followed by a 300 ms random noise mask, and then the second face appeared on the screen until the participant responded by pressing the "s" or the "d" key of the keyboard to indicate if the two faces were exactly the same or different, respectively.

RESULTS

For each task, patient's accuracy (% correct) and reaction times on correct trials (ms) were compared to those of the control group using ANOVAs with additional within-subject factors for the conditions within each task.

The Famous Faces Task

We first ran a multivariate analysis of variance (MANOVA) on the results collected from this task that takes into account the variance–covariance between variables. Indeed some of the dependent variables of this task were strongly related to each other. The MANOVA on participants' accuracy (% correct) with the different CONDITIONS (famous faces, corrected famous face and non-famous faces) as dependent variables and the GROUP as the fixed factor indicated a difference between GROUPS for the famous face condition and the corrected famous face condition (ps $< .05$), but not for the non-famous face condition ($F(1, 34) = 1.692$, $p = .202$).

A simple ANOVA on participants' accuracy with the CONDITION (famous faces and non-famous faces) as the within-subject factor and the GROUP as the between-subjects factor confirmed this result and revealed, for the famous face condition and the corrected famous face condition a main effect of CONDITION [uncorrected: $F(1, 34) = 40.846$, $p < .0001$; corrected: $F(1, 34) = 21.712$, $p < .0001$], a main effect of GROUP [uncorrected: $F(1, 34) = 17.725$, $p < .0001$; corrected: $F(1, 34) = 22.127$, $p < .0001$] and an interaction between the CONDITION and the GROUP [uncorrected: $F(1, 34) = 8.307$, $p = .007$; corrected: $F(1, 34) = 10.707$, $p = .002$].

Follow-up analyses (two-tailed independent sample t-tests) for each CONDITION separately indicated that cataract-reversal patients differed significantly from controls when they had to recognize famous faces [44% ($SE = 1$) vs. 78% ($SE = 4$); $t(15.602) = -3.12$, $p = .007$] but not when they had to reject the non-famous faces [93% ($SE = 3$) vs. 97% ($SE = 1$); $t(12.832) = -1.009$, $p = .331$] (Fig. 1). Although patients' accuracy in recognizing famous faces increased to 63% ($SE = .09$) when restricted to the faces they reported knowing, it was still substantially and significantly lower than the corrected accuracy of controls ($X = 92\%$; $SE = 2$); $t(12.361) = -3.217$, $p = .007$ (Fig. 1).

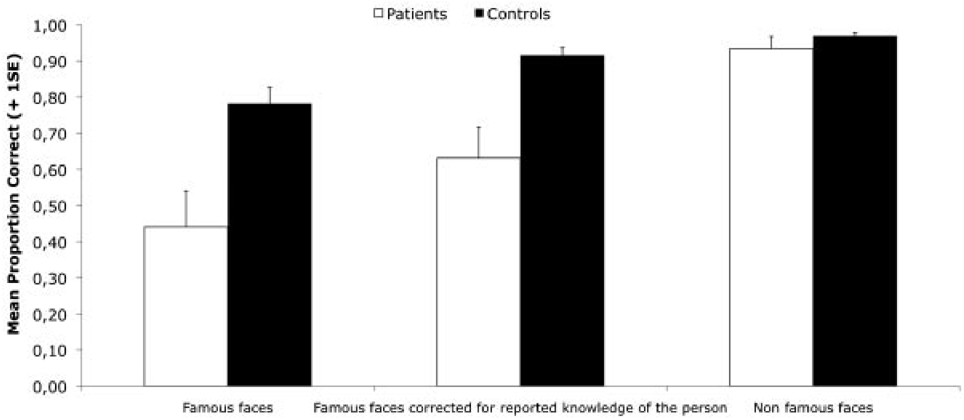

FIGURE 1 Mean proportion of correct responses of cataract-reversal patients (white bars) and of controls (black bars) for the famous condition (corrected and non-corrected scores) and for the non-famous condition of the Famous Faces Task. Shown are the between-subjects standard errors.

The Cambridge Face Memory Test

The MANOVA on participants' accuracy (% correct) with the different CONDITIONS (introduction, no noise, noise) as dependent variables and the GROUP as the fixed factor showed a difference between GROUPS for all the conditions of this task (*p*s $< .05$). More specifically, the ANOVA on their accuracy with the CONDITION (introduction, no noise, noise) as a within-subject factor and the GROUP as a between-subjects factor revealed a main effect of CONDITION ($F(2, 68) = 127.418$, $p < .0001$), a main effect of GROUP ($F(1, 34) = 15.505$, $p < .0001$), but no interaction between the CONDITION and the GROUP ($F(2, 68) = .897$, $p = .413$). Post hoc *t*-tests corrected for multiple comparisons (Bonferroni corrections) indicated that the effect of CONDITION arose because participants did much better on the introduction than on the no noise condition and the noise condition (*p*s $< .05$). Although patients' accuracy was above chance even on the hardest condition [44% ($SE = 16$) in the noise condition; chance level 33%], it was significantly worse than that of controls even in the easy introductory condition [87% ($SE = 5$) vs. 98% ($SE = .07$); $t(11.497) = -2.208$, $p = .048$] (Fig. 2A).

The MANOVA on participants' correct reaction times (ms) with the different CONDITIONS (introduction, no noise, noise) as dependent variables and the GROUP as the fixed factor showed, as for accuracy, that cataract-reversal patients were slower than controls for all conditions (*ps* $<.05$). Specifically, the ANOVA on their correct reaction times indicated a main effect of CONDITION ($F(1.299, 44.182) = 15.334$, $p < .0001$), a main effect of GROUP ($F(1, 34) = 39.065$, $p < .0001$) and, as for accuracy, no significant interaction between the CONDITION and the GROUP ($F(1.299, 44.182) = 3.313$, $p = .065$). The effect of CONDITION arose because participants were faster on the introduction than on the no noise condition and the noise condition of the test (post hoc *t*-tests with Bonferroni correction; *p*s $< .005$), with no difference between the latter two conditions of the test (post hoc *t*-test with Bonferroni correction; $p > .05$). Patients' correct reaction times (4,790 ms overall; $SE = 1{,}521$) were generally much slower than those of controls (2,642 ms overall; $SE = 540$; Fig. 2B).

Prosopagnosic Questionnaire

Because of the nature of the questionnaire, we performed Mann–Whitney's *U* non-parametric tests on participants' ratings for the whole test and for each question separately. Overall, cataract-reversal patients rated themselves in the same range as control participants ($U = 96$, $p = .104$). They also rated themselves on most questions as having the same skill as did the control group (*p*s $> .05$). There were two exceptions, one implying that patients have the impression of worse face memory and the other implying an impression of better face memory. Specifically, for Question 2 ("In general, do you have the impression of being less accurate than other people in recognizing familiar faces (family, friends, celebrity...)"; $U = 53$, $p = .002$), patients gave significantly higher ratings than controls, whereas for Question 6 ("Do you think you are very good at recognizing faces?"; $U = 78.5$, $p = .026$), they surprisingly also gave higher ratings than controls.

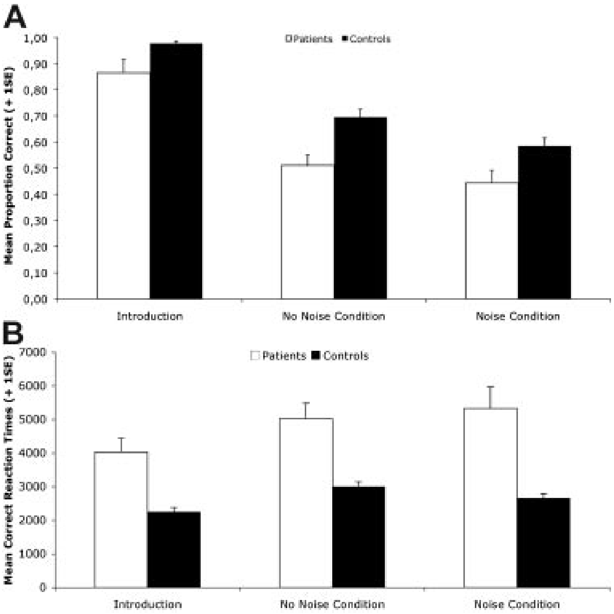

FIGURE 2 Mean proportion of correct responses (A) and correct reaction times (B) of cataract-reversal patients and of controls for the introduction, the no noise condition and the noise condition of the Cambridge Face Memory Test. Shown are the between-subjects standard errors.

The Composite Face Task

The MANOVA on participants' accuracy (% correct) with the different CONDITIONS [aligned same (AS), aligned different (AD), misaligned same (MS), misaligned different (MD)] as dependent variables and the GROUP as the fixed factor revealed no difference between the GROUPS for these conditions (*p*s > .05). However, when we focused on participants' composite face effect by performing an ANOVA on their accuracy, there was a main effect of the ALIGNMENT of the face parts ($F(1, 34) = 16.313$, $p < .0001$) for trials of interest (''same'' decision; aligned same vs. misaligned same trials), such that they were better at matching the upper parts of faces on misaligned (MS) than on aligned (AS) trials. Conversely, there was no effect of ALIGNMENT for different trials [aligned different (AD) vs. misaligned different (MD): $F(1, 34) = 2.836$, $p = .101$]. The two GROUPS (patients vs. controls) did not perform statistically differently on same trials ($F(1, 34) = .128$, $p = .723$) or on different trials ($F(1, 34) = 4.034$, $p = .053$) and did not differ in terms of the magnitude of their composite face effect for same and different trials, as evidenced by the absence of interaction between the GROUP and the ALIGNMENT of the face parts for same trials ($F(1, 34) = .028$, $p = .867$) and for different trials ($F(1, 34) = .056$, $p = .814$) (Fig. 3A). Subsequent analyses for each GROUP of participants separately on same trials (two-tailed paired *t*-tests) revealed a significant composite effect (lower accuracy for aligned than misaligned trials) for cataract patients ($t(11) = -2.306$, $p = .042$) as well as for controls with normal vision ($t(23) = -3.694$, $p = .001$).

Contrary to what was observed for accuracy, the MANOVA on participants' correct reaction times (ms) with the different CONDITIONS [aligned same (AS), aligned different (AD), misaligned same (MS), misaligned different (MD)] as dependent variables and the GROUP as the fixed factor indicated a difference between GROUPS for all conditions (*p*s < .05). The ANOVA on their correct reaction times indicated a main effect of the ALIGNMENT of the face halves ($F(1, 34) = 23.725$, $p < .0001$), participants being, as expected in the case of a composite face effect, faster in the MS condition than in the AS condition. Conversely, there was no effect of ALIGNMENT for different trials (AD vs. MD: $F(1, 34) = 1.513$, $p = .227$). For both same and different trials, there was a difference between the GROUPS because patients were generally slower at the task than controls [same trials: 792

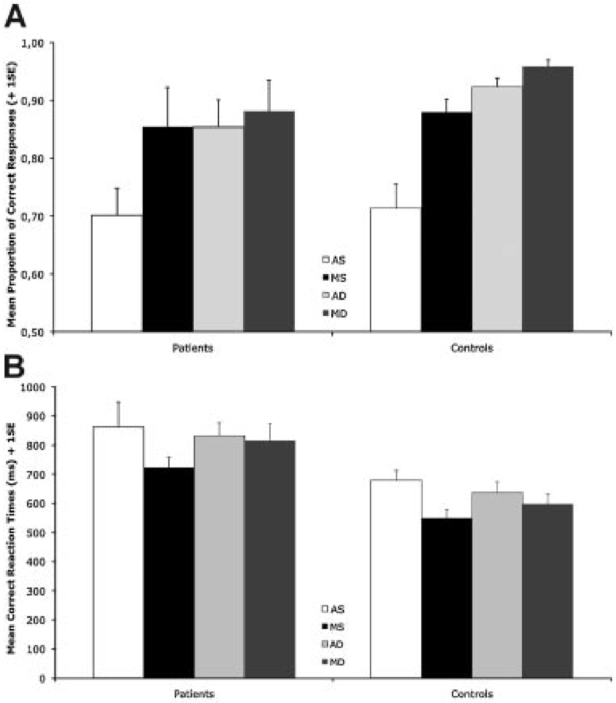

FIGURE 3 Mean proportion of correct responses (A) and correct reaction times (B) of cataract-reversal patients and of controls in the aligned same (AS) condition, the misaligned same (MS) condition, the aligned different (AD) condition and the misaligned different (MD) condition. Shown are the between-subjects standard errors.

vs. 614 ms: $F(1,\ 34) = 9.705$, $p = .004$; different trials: 824 vs. 617 ms: $F(1,\ 34) = 12.483$, $p = .001$]. There was no interaction between the ALIGNMENT of the face parts and the GROUP for same trials ($F(1,\ 34) = .025$, $p = .876$) or for different trials ($F(1,\ 34) = .282$, $p = .599$), as there would be if the magnitude of the composite face effect differed between the two groups (Fig. 3B). Subsequent analyses for each group separately on same trials (two-tailed paired *t*-tests) revealed a significant composite effect (faster reaction times for misaligned than aligned trials) in cataract patients ($t(11) = 2.486$, $p = .03$) and in controls ($t(23) = 4.731, p < .0001$).

The Benton Facial Recognition Task

The MANOVA on participants' accuracy (% correct) with the different PARTS (Part 1, Part 2) as dependent variables and the GROUP as the fixed factor showed a difference between GROUPS for Part 2 ($F(1,\ 34) = 15.555$, $p < .0001$) but not for Part 1 ($F(1,\ 34) = .274$, $p = .604$). In the same line, the ANOVA on their accuracy indicated a main effect of the PART of the test (Part 1 = 94% > Part 2 = 74%; $F(1,\ 34) = 61.132$, $p < .0001$), a main effect of GROUP (Patients = 80% < Controls = 88%: $F(1,\ 34) = 7.003$, $p = .012$) and an almost significant interaction between the PART of the test and the GROUP ($F(1,\ 34) = 3.978$, $p = .054$) because of the larger difference between the groups for Part 2 [two-tailed independent sample *t*-test: $t(34) = -3.944$, $p < .0001$] than for Part 1 [two-tailed independent sample *t*-test: $t(34) = -.523, p = .604$].

The MANOVA on participants' correct reaction times (ms) with the different PARTS (Part 1, Part 2) as dependent variables and the GROUP as the fixed factor indicated a difference between GROUPS for both parts of the test (*p*s < .05). As expected, the ANOVA on their correct reaction times showed a main effect of the PART of the test (Part 1 = 4,052 ms < Part 2 = 4,465 ms; $F(1,\ 34) = 4.738$, $p = .037$), a main effect of GROUP [Patients = 5,565 ms < Controls = 2,952 ms; $F(1,\ 34) = 20.596$, $p < .0001$] and, no interaction between the PART of the test and the GROUP ($F(1,\ 34) = 2.695$, $p = .110$; Fig. 4B).

The Monkey Jane Task

The MANOVA on participants' accuracy (% correct) with the different CONDITIONS (human upright, human inverted, monkey upright, monkey inverted) as dependent variables and the GROUP as the fixed factor revealed a difference between GROUPS for all conditions (*p*s <.05) except for the monkey inverted condition ($F(1,\ 34) = 1.617$, $p = .212$). The ANOVA on participants' accuracy revealed a main effect of SPECIES [human vs. monkey: $F(1,\ 34) = 13.440$, $p = .001$] and a main effect of ORIENTATION [upright vs. inverted: $F(1,\ 34) = 32.560$, $p < .0001$], participants being better at matching human faces than monkey faces and better at matching upright faces than inverted faces based on feature spacing.[1] There was no main effect of GROUP [patients vs. controls: $F(1,\ 34) = 1.746$, $p = .195$]. However the triple interaction including the SPECIES, the ORIENTATION of the stimulus and the GROUP ($F(1,\ 34) = 8.965$, $p = .005$), as well as the interaction between the ORIENTATION and the GROUP ($F(1,\ 34) = 20.091$, $p < .0001$), reached significance. There was no interaction between the SPECIES and the GROUP ($F(1,\ 34) = 3.171$, $p = .084$) or between the SPECIES and the ORIENTATION of the face ($F(1,\ 34) = 1.415$, $p = .243$).

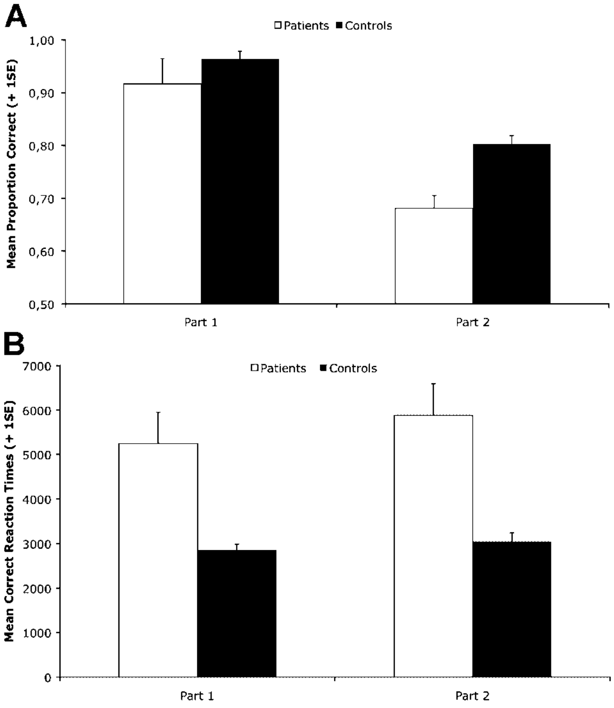

FIGURE 4 Mean proportion of correct responses (A) and correct reaction times (B) of cataract-reversal patients and of controls for Part 1 and Part 2 of the Benton Face Recognition Test. Shown are the between-subjects standard errors.

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[1] We did not find any effect of GROUP or interaction involving the GROUP factor on non-manipulated human and monkey faces (*p*s > .05).

As a follow-up on this triple interaction, we conducted simple ANOVAs for each SPECIES separately. For monkey faces, there was a significant main effect of ORIENTATION (better for upright: $F(1, 34) = 9.410$, $p = .004$), no main effect of GROUP ($F(1, 34) = 3.317$, $p = .077$) and no significant interaction between the ORIENTATION of the face and the GROUP ($F(1, 34) = .630$, $p = .433$). Conversely, for human faces, there was a significant main effect of ORIENTATION (better for upright: $F(1, 34) = 20.051$, $p < .0001$), no main effect of GROUP ($F(1, 34) = .156$, $p = .696$) but a significant interaction between the ORIENTATION of the face and the GROUP ($F(1, 34) = 28.840$, $p < .0001$). This interaction arose because patients did not show a significant effect of ORIENTATION on this face category ($F(1, 11) = .087$, $p = .774$), whereas controls did ($F(1, 24) = 70.813$, $p < .0001$). Specifically patients were significantly worse than controls in matching upright human faces (two-tailed independent sample *t*-test: $t(34) = -2.704$, $p = .011$) and significantly better than controls in matching inverted human faces (two-tailed independent sample *t*-test: $t(34) = 2.519$, $p = .017$; Fig. 5A).

The MANOVA on participants' correct reaction times (ms) with the different CONDITIONS (human upright, human inverted, monkey upright, monkey inverted) as dependent variables and the GROUP as the fixed factor revealed a difference between GROUPS for all conditions (*p*s >.05). The ANOVA performed on their correct reaction times revealed no main effect of SPECIES ($F(1, 34) = 1.246$, $p = .272$) and no main effect of ORIENTATION ($F(1, 34) = 2.364$, $p = .133$). However the interaction involving SPECIES and ORIENTATION reached significance ($F(1, 34) = 9.020$, $p = .005$). Simple ANOVAs for each SPECIES separately indicated a significant effect of orientation for human faces (U*p* = 1,091 ms, INV = 1,237 ms; $F(1, 35) = 7.573$, $p = .009$) but not for monkey faces (U*p* = 1,140 ms, INV = 1,103 ms; $F(1, 35) = .266$, $p = .609$; Fig. 5B). There was also a main effect of GROUP ($F(1, 34) = 14.859$, $p < .0001$), cataract-reversal patients being generally slower than controls at the task, but no other significant interaction involving the GROUP factor (*p*s > .05).

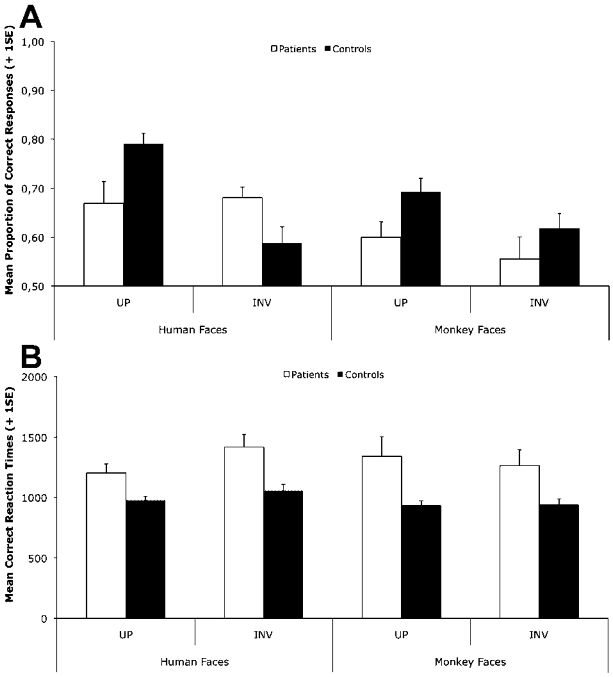

FIGURE 5 Mean proportion of correct responses (A) and correct reaction times (B) of cataract-reversal patients and of controls when matching the upright and inverted human faces as well as the upright and inverted monkey faces of the Monkey Jane task. Shown are the between-subjects standard errors.

Correlation Analyses

In order to determine whether patients' results on the perceptual tasks (Composite Face Task, Benton test, Monkey Jane Task) predicted their results in face memory (Famous Faces task, Cambridge Face Memory test), we translated their scores into standardized *z*-scores on each task. Specifically, we took each patient's accuracy, subtracted controls' mean accuracy in that condition, and divided this number by controls' standard deviation. Negative accuracy in *z*-scores indicates a deficit compared to controls and positive *z*-scores reflect above-average performance. We used the same calculation for correct reaction times but reversed the sign so that negative scores indicated, as for accuracy, a deficit compared to controls. For these correlations, we chose the most representative index for each task. Specifically, we used patients' composite face effect on same trials (MS-AS, as in Le Grand et al., 2004), their results on Part 2 of the Benton test (the only part of the test involving the recognition of faces in novel viewpoints) and their results on the Monkey Jane Task for upright human faces as possible predictors of their averaged accuracy on the Famous Faces Task and on the Cambridge Face Memory test. None of the perceptual *z*-scores were correlated with the *z*-scores in face memory (Pearson one-tailed correlations: *p*s > .05), despite considerable variance on each of the measure.

We also assessed the correlation between patients' *z*-scores on these measures and three variables that might affect their performance: the duration of their initial deprivation, their age at testing, and the log of their visual acuity in the better eye. We used one-tailed

Spearman coefficients instead of one-tailed Pearson coefficients when the analyses included the age at testing because it was not normally distributed according to the Shapiro–Wilk test of normality ($p = .011$). With two exceptions, none of these measures was correlated with patients' duration of deprivation, their age at testing or their visual acuity in the better eye (ps $> .05$). The first exception was for the correlation between patients' accuracy on the second part of the Benton test and the duration of their deprivation period ($r = .512$, $p = .044$). Specifically, the longer the deprivation period, the worse was the patients' performance. The second exception was for the correlation between patients' accuracy on the Cambridge Face Memory test and their visual acuity in the better eye ($r = -.553$, $p = .031$), suggesting that the worse their visual acuity, the worse they were on the Cambridge test. Analysis of each part of the test separately indicated that the correlation was present for the introductory part of the test ($r = -.605$, $p = .019$) and the no noise condition ($r = -.610$, $p = .018$) but not the noise condition ($r = -.495$, $p = .051$).

DISCUSSION

In this study, we showed for the first time that early visual deprivation leads to a deficit in remembering faces: patients who missed early visual input because of dense bilateral cataracts showed a deficit in recognizing famous and recently learned faces. Specifically, patients were significantly impaired compared to controls in the Famous Faces Task, whether we analyzed the raw scores or corrected their accuracy for their familiarity with the face, as indexed by whether they thought when seeing the person's name that they would be able to recognize that person's face. The fact that the deficit was also present when corrected for self-reported familiarity with the face rules out a simple explanation based on patients' having avoided TV or facial images in newspapers and magazines because of perceptual deficits. Cataract-reversal patients were also significantly worse and much slower than controls at recognizing recently learned faces on the Cambridge Face Memory Task, whether those faces were tested with or without superimposed noise. Their proportion of correct responses in the three conditions of the Cambridge Face Memory Task (introduction: 87%; no noise: 51%; noise: 44%) was very similar to those of the developmental prosopagnosic patients tested by Duchaine and Nakayama (2006) (introduction: 85%; no noise: 47%; noise: 36%). They were also much slower than controls in every condition.

The correlation of the deficits in the Cambridge Face Memory test with acuity raises the possibility that early deprivation impacts face memory indirectly by limiting the information that patients can pick up from faces during development and/or during the test. We cannot rule out this possibility but think it is unlikely to be the sole explanation because acuity was not correlated with performance on any of the perceptual tasks or with the deficits on the Famous Faces Task. Moreover, patients' normal accuracy in discriminating between monkey faces and between misaligned faces as well as their superior accuracy in discriminating between inverted human faces argue against the hypothesis that the deficits in other conditions arose from limits on the visibility of the faces from poor visual acuity. Evidence that normal observers make little use of high spatial frequencies when distinguishing and remembering faces (Gao & Maurer, 2011; Näsänen, 1999), combined with evidence that cataract-reversal patients have normal or nearly normal contrast sensitivity for low- and mid-spatial frequencies (Ellemberg, Lewis, Maurer, Lui, & Brent, 1999) also argues against the poor visibility explanation. Even for the Cambridge Face Memory test, a large deficit was apparent in the patient with the best visual acuity (i.e., M3: 20/25 in the better eye, a value that is nearly normal). Similarly, other problems, such as nystagmus and strabismus, might have degraded patients' recognition of the facial images used in the Famous Face Task and the Cambridge Face Memory test, but there did not seem to be a relationship between the presence of any of these secondary complications and patients' performance on the tests, at least within this small sample. Moreover, patients viewed the stimuli binocularly, and hence, with the dominant or fixating eye in use and latent nystagmus minimized.

Despite their deficits on the two face memory tasks, patients did not differ from controls in their self-assessment of their face memory. There was no significant difference for 8 of the 10 questions and for the remaining two, patients rated their memory as both inferior and superior to that of controls. In this way they are very different from patients with acquired prosopagnosia, who often complain about their inability to recognize faces, comparing their performance with that prior to the accident (e.g., Busigny & Rossion, 2010). Rather, they resemble more closely individuals with congenital/developmental prosopagnosia, some of whom are unaware of their deficit, perhaps because their face perception never underwent a dramatic change and because they have had a lifetime to develop compensatory strategies (Behrmann & Avidan, 2005).

Cataract-reversal patients were also less accurate than controls on two of the three perceptual tasks. First, patients showed a deficit compared to controls in the Monkey Jane Task. Specifically they were less accurate and slower than controls in discriminating between upright human faces that differed only in the spacing of features, with no significant difference in accuracy for discriminating such differences in monkey faces, as in previous studies (Le Grand et al., 2001; Robbins et al., 2010). In line with recent findings using contingent face after effects (Robbins, Maurer, Hatry, Anzures, & Mondloch, 2012), they were also better than controls in making these judgments for inverted human faces, with no sign of the usual inversion decrement. However, it must be noted that they were also slower than controls in all conditions, making their superiority for inverted human faces and the absence of a face inversion effect difficult to gauge. Second, patients showed a deficit compared to controls on the Benton test in line with the results of Geldart et al. (2002) and Putzar, Hötting, and Röder (2010). They were significantly slower and worse than the control group in matching unfamiliar faces presented simultaneously on the screen with a change of point of view between the target and the probes. Unlike the results of Geldart et al. (2002), their deficit also increased as their deprivation period increased. One possible reason is that the distribution of deprivation periods was shifted toward shorter durations in the current sample and the adverse effects of early deprivation may be mitigated only when the deprivation is very short, with no difference in the size of the deficit for periods of medium and long duration. Third and contrary to our initial prediction based on the study of Le Grand et al. (2004), patients were normal on the Composite Face Task. They showed a composite face effect of the same magnitude as controls for both accuracy and reaction times, while also being slower than controls in all conditions. We speculate that the difference between these results and those collected by Le Grand et al. (2004) reflects a delay in the acquisition of the composite effect in cataract-reversal patients, rather than a permanent deficit. The group tested here was significantly older than the one tested by Le Grand et al. [21 vs. 15 years; $t(22) = 2.514$, $p = .020$], with no mean difference in the duration of their visual deprivation [139 vs. 125 days; $t(22) = -.719$, $p = .480$] or their visual acuity in the better eye [.3 vs. .4; $t(15.431) = .827$, $p = .421$]. Furthermore, three patients tested in both experiments showed an increase in the magnitude of their composite effect of more than 20% over the intervening 8- to 9-year period (Tab. 3). In other words, it seems that missing visual input during early infancy, a period when the infant with normal eyes is thought to acquire holistic face processing (Turati, Di Giorgio, Bardi, & Simion, 2010), delays the acquisition of this process by many years. This hypothesis could be evaluated by testing a larger cohort of cataract-reversal patients repeatedly in order to determine the age at which they first show a composite effect and how long it takes for the composite effect to become of normal magnitude.

Despite the lack of correlation between the perceptual and memory deficits at the time of the test within this small sample, they may have been related during development. Patients treated for bilateral congenital cataract show deficits in differentiating between faces based on the spacing between their internal features, a deficit that is manifest as early as 14 years of age, the youngest age tested (Le Grand et al., 2001) and that persists into adulthood (this study). Instead they process the features of faces as easily as normal controls (Le Grand et al., 2001; Mondloch et al., 2010). Because they do not notice variations in feature spacing and fail to process faces holistically until late in development, cataract-reversal patients are unlikely to develop a normal multi-dimensional face space centered on a norm (Valentine, 1991). Their representations are not likely to be as well-differentiated as those of controls and may be grouped by featural similarity rather than with reference to a norm. However, because they can recognize faces based on featural and external differences as well as their peers, they may be unaware of their memory deficiency. When holistic processing finally emerges after adolescence, it may be too late to alter

Table 3. The Composite Face Effect of Three Cataract-Reversal Patients Tested in Le Grand et al. (2004) and Re-Tested as Part of the Current Study, Which Took Place 8–9 Years Later

		Age at Test (Years)		Le Grand et al. (2004)			This Study		
		Le Grand et al. (2004)	This Study	AS Condition (%)	MS Condition (%)	CFE (MS-AS)	AS Condition (%)	MS Condition (%)	CFE (MS-AS)
CP	M	20	29	.77	.77	.00	.75	.96	.21
MD	F	21	30	.81	.85	.04	.58	.88	.30
MO	F	10	18	.83	.83	.00	.75	.96	.21

Their composite effect, measured as the difference in accuracy between the misaligned same (MS) condition and the aligned same (AS) condition, increased over time. This pattern suggests a delay in the acquisition of the composite effect after early visual deprivation.

the basic structure of their memory representations. Given these speculations, it may seem surprising that the correlation analyses involving patients' *z*-scores on the perceptual tasks were not good predictors of their deficits in face memory. It is however possible that the true correlations are too small to emerge in our small sample and/or that they become evident only when individual differences in general cognitive and visual processing are taken into account, as it is true for the composite face effect and face memory in visually normal subjects (Wang, Li, Fang, Tian, & Liu, 2012). Alternatively, it is possible that the perceptual skills that emerge in children with normal eyes during infancy or the preschool years (e.g., holistic processing, sensitivity to feature spacing) are necessary but not sufficient to build normally robust face representations. Future studies could test this prediction by following children treated for bilateral congenital cataract longitudinally during the preschool and school-aged years to see whether the memory deficits emerge and grow as soon as the perceptual deficits are evident.

Cataract-reversal patients' memory deficits documented here may be specific to upright human faces, as found previously for the deficits in sensitivity to feature spacing (Robbins et al., 2010), or they may extend to memory for other object categories. Future studies using the structure of the Cambridge Face Memory Task to present specific objects for recognition would be useful as a comparison. One possibility is that the delayed development of holistic processing represents a general problem with feature binding that has wider impact. That possibility is consistent with previous evidence that adults treated for bilateral congenital cataracts show deficits in integrating audio and visual events, whether they came from flashes and beeps or faces and voices (Putzar, Hötting, Rösler, & Röder, 2007).

NOTES

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