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PAPER

The effect of early visual deprivation on the development of face processing

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Abstract

We evaluated the importance of early visual input for the later development of expertise in face processing by studying 17 patients, aged 10 to 38 years, treated for bilateral congenital cataracts that deprived them of patterned visual input for the first 7 weeks or more after birth. We administered five computerized tasks that required matching faces on the basis of identity (with changed facial expression or head orientation), facial expression, gaze direction and lip reading. Compared to an age-matched control group, patients' recognition of facial identity was impaired significantly when there was a change in head orientation (e.g. from frontal to tilted up), and tended to be impaired when there was a change in facial expression (e.g. from happy to surprised). Patients performed normally when matching facial expression and direction of gaze (e.g. looking left or right), and in reading lips (e.g. pronouncing 'u' or 'a'). The results indicate that visual input during early infancy is necessary for the normal development of some aspects of face processing, and are consistent with theories postulating the importance of early visual experience (de Schonen & Mathivet, 1989; Johnson & Morton, 1991) and separate neural mediation of different components of face processing (Bruce & Young, 1986).

Introduction

Adults are 'experts' in face processing: they can recognize thousands of individual faces rapidly and accurately, and they can easily recognize specific aspects of a single face, including emotional expression, head orientation, direction of gaze and sound being mouthed (Bahrick, Bahrick & Wittlinger, 1975; see Bruce & Young, 1986 for a review). Neurophysiological studies in normal adult humans and non-human primates have shown that specific regions of the temporal cortex, particularly in the right hemisphere, are important for some of these aspects of face processing (e.g. Allison, Ginter, McCarthy, Nobre, Puce, Luby & Spencer, 1994; Baylis, Rolls & Leonard, 1985; de Renzi, 1986; Gauthier, Skudlarski, Gore & Anderson, 2000; Kanwisher, McDermott & Chun, 1997; Perrett, Hietanen, Oram & Benson, 1992; Perrett, Rolls & Cann, 1982; Puce, Allison, Gore & McCarthy, 1995; Rolls, 1984; Sergent, Ohta & Macdonald, 1992). These data are supported by neuropsychological studies of adult patients with lesions confined to the left or right side of the temporal cortex. Patients with damage in the right hemisphere have difficulty classifying facial expressions and recognizing faces but preserved ability to read lips; patients with comparable damage in the left hemisphere can recognize facial identity but are impaired in lip reading (Campbell, Landis & Regard, 1986; de Renzi, Perani, Carlesimo, Silveri & Fazio, 1994; Mandel, Tandon & Asthana, 1991; Yin, 1970; see Bruce & Young, 1986 for a review).

Adults' expertise develops slowly: children around 6 years of age are less skilled than adults in recognizing individual faces, and in some comparisons, perform as poorly as adult patients with right hemisphere damage (Carey & Diamond, 1980; Carey, Diamond & Woods, 1980; Flin, 1980; Goldstein & Chance, 1964). For example, in a memory task in which subjects are shown photographs of faces for 5 seconds each, and then are asked to choose those faces from a larger set, 6-year-olds perform at chance whereas adults perform at ceiling

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levels (Carey *et al.*, 1980). Even when memory demands are minimized by reducing the size of the stimulus set or by testing children with matching tasks, children do not perform in the adult range until about 10 years of age (Carey & Diamond, 1994; Diamond & Carey, 1977). Although children as young as 5 years of age are proficient in identifying faces' sex and emotional expression when viewing familiar faces (Ellis, Ellis & Hosie, 1993), even at age 6 they are much poorer than adults in identifying emotional expression in unfamiliar faces, in lip reading, decoding direction of gaze and in recognizing faces despite changed head orientation or facial expression (Geldart, 2000; Geldart, Mondloch, Maurer, de Schonen, Lewis & Brent, 1998). These abilities become adultlike only sometime between 6 and 10 years of age.

Despite this slow development, many face processing skills are present during infancy. Newborns are drawn towards face-like patterns over non-face patterns (Goren, Sarty & Wu, 1975; Johnson, Dziurawiec, Ellis & Morton, 1991; Mondloch, Lewis, Budreau, Maurer, Dannemiller, Stephens & Kleiner-Gathergoal, 1999; Valenza, Simion, Cassia & Umiltà, 1996), they prefer attractive over unattractive faces (Slater, von der Schulenberg, Brown, Badenoch, Butterworth, Parsons & Samuels, 1998; Slater, Bremner, Johnson, Sherwood, Hayes & Brown, 2000) and they can recognize their mother's face if the external features (i.e. hair) are present (Bushnell, Sai & Mullen, 1989; Pascalis, de Schonen, Morton, Deruelle & Fabre-Grenet, 1995) and are able to recognize an unfamiliar face after a 2-minute delay (Pascalis & de Schonen, 1994). Additional skills begin to emerge between 2 to 4 months of age. Infants 2 to 4 months old recognize individual faces based on the internal features alone (Bartrip, Morton & de Schonen, 2001). By 3 months, infants recognize a face posing with different head orientations, even after a 24-hour delay (e.g. Pascalis, de Haan, Nelson & de Schonen, 1998), and differentiate some facial expressions (e.g. happy vs. sad or surprise) (e.g. Barrera & Maurer, 1981; Young-Browne, Rosenfeld & Horowitz, 1977). Three-month-olds also can form a mental prototype of a face and, like adults, treat it as more familiar than the individual faces from which it was formed (e.g. de Haan, Johnson, Maurer & Perrett, 2001). By 4 months, infants demonstrate discrimination of the direction of eye gaze (e.g. gaze frontal vs. 45° left) (e.g. Hains & Muir, 1996; Hood, Willen & Driver, 1998; Vecera & Johnson, 1995). These emerging abilities likely reflect cortical development (Atkinson, Hood, Wattam-Bell, Anker & Tricklebank, 1988; Bronson, 1974; Maurer & Lewis, 1979) and increased cortical specialization. At 2 months of age, faces, but not a circle of diodes, activate the right fusiform gyrus (Tzourio-Mazoyer, de Schonen, Crivello, Reutter, Aujard & Mazoyer, 2002) – which is also a characteristic of cortical activations observed in adults. Furthermore, 4- to 9-month-olds discriminate between a stranger's face and the mother's face better when the faces are presented in the left visual field (i.e. projected primarily to the right hemisphere) (de Schonen, Gil de Diaz & Mathivet, 1986), and they learn to discriminate faces and geometric patterns that differ primarily in spatial configuration better when the stimuli are presented in the left visual field (Deruelle & de Schonen, 1995, 1998), but can discriminate faces and patterns that differ primarily in local features better when those stimuli are presented in the right visual field (i.e. projected to the left hemisphere) (Deruelle & de Schonen, 1995, 1998) – a pattern consistent with adult hemispheric specialization (e.g. Allison *et al.*, 1994; Hillger & Koenig, 1991; Sergent *et al.*, 1992).

Recent theories suggest that experience with faces during the first weeks of life sets up a neural architecture that will become specialized for various aspects of face processing over the subsequent months and years (de Schonen, 1989; de Schonen & Mathivet, 1989; Johnson & Morton, 1991; Morton & Johnson, 1991). According to these theories, a primitive, subcortical system causes newborns to orient preferentially toward face-like patterns over non-face stimuli (e.g. Goren *et al.*, 1975; see 'Conspec' in Johnson *et al.*, 1991) and facilitates species recognition (de Schonen & Mathivet, 1989). This early system exposes newborns to faces at a short distance, and consequently, may facilitate the emergence of a separate cortical system that underlies the recognition of individual faces. Early visual experience is also critical according to de Schonen and Mathivet (1989). According to their theory, young infants' poor visual acuity and contrast sensitivity (e.g. Banks & Salapatek, 1981; Mayer, Beiser, Warner, Pratt, Raye & Lang, 1995; see Maurer & Lewis, 2001 for a review) limit the encoding of objects to information that is carried by low spatial frequencies. As a result, young infants should be sensitive to the spatial relations among facial features, but relatively insensitive to the fine details of the features. de Schonen (de Schonen, Deruelle, Mancini & Pascalis, 1993; de Schonen & Mathivet, 1989) argues that the developing cortical networks that will eventually become specialized for configural processing of such objects are more likely to develop in the right hemisphere because the right hemisphere matures at a faster rate than the left hemisphere during this period of early infancy (e.g. Rosen, Galaburda & Sherman, 1987) when visual input is limited to lower spatial frequencies, and when that input is not yet transferred between hemispheres via the corpus callosum (e.g. de Schonen & Mathivet, 1990; Liegeois, Bentejac & de Schonen, 2000). If these theories are correct, then the absence of visual experience during a critical period in infancy may cause aberrations in the cortical mechanisms that govern adult face processing, particularly in those in the right hemisphere involved in configural processing.

The purpose of our study was to explore the influence of early visual experience on the development of the adult-level specialization for face processing, by studying patients who were treated for bilateral congenital cataracts that had deprived them of patterned visual input during early infancy. The patients, aged 10 to 38, had been born with a dense and central opacity in the lens of both eyes that prevented patterned stimulation from reaching the retina. They were treated by surgical removal of the natural lenses and fitting of the eyes with contact lenses that focused visual input on the retina (see Maurer, Lewis & Brent, 1989). All of the patients were treated during infancy and had had at least 10 years of visual experience after treatment prior to our tests. Their results were compared to an age-matched control group with a history of normal visual experience.

This was the first study to examine the effects of early visual deprivation on the development of face processing. Because we did not know whether the patients would have only subtle deficits in a few face processing skills, large deficits in most skills or no deficits at all, we constructed a battery of tasks to probe a large number of skills. Our face perception test battery was adapted from one that showed differential deficits across tasks both in children with congenital brain damage and in autistic children (Gepner, de Gelder & de Schonen, 1996; Mancini, de Schonen, Deruelle & Massoulier, 1994). Their deficits were related to the site and hemisphere of brain damage, as would be expected from the evidence that various components of face processing are controlled by separate cortical systems (e.g. Bruce & Young, 1986). In our version, a single face appeared on a computer screen for 2 seconds, followed by a choice of three faces, and participants were asked to move a joystick to indicate which of the three faces matched the original in: (1) identity despite changes in facial expression, (2) identity despite changes in head orientation, (3) facial expression despite changes in the face's identity, (4) vowel sound being mouthed despite changes in the face's identity and (5) direction of gaze despite changes in the face's identity and head orientation. To encourage processing of internal features and to discourage reliance on unusual facial markings, we had models wear identical scarves that covered the hair and ears, we matched the faces to-be-compared on complexion and the shape of the outer contour, and used computer software to remove natural facial markings.

Method

Participants

All participants and all of the stimulus faces were Caucasian so that the results would not be influenced by variability in participants' familiarity with other races (e.g. see O'Toole, Peterson & Deffenbacher, 1996, for the 'other race' effect). We included only subjects who reported being right-handed because some face processing skills are lateralized (e.g. Deruelle & de Schonen, 1998).

Patients

There were 17 patients treated for bilateral congenital cataracts, all of whom were at least 10 years of age at the time of testing (*M* age: 16 years; range: 10.9–38.5 years). Patients met each of the following criteria: dense and central cataracts in both eyes diagnosed on their first eye examination and by 6 months of age; no abnormalities in the ocular media or the retina; no untreated ocular disease, such as glaucoma; and optical correction of the eyes after surgery for at least 75% of the time until the test. We included patients with common associated abnormalities such as microcornea (small cornea), strabismus (misalignment of the eyes), nystagmus (repetitive, jerky movements of the eye) or glaucoma that had been treated successfully by medication with no sign of optic nerve damage. Table 1 provides clinical details of the patients.

We assumed that any child who had dense central cataracts diagnosed on the first eye exam and before 6 months of age had been deprived from birth because it would be unusual to have dense cataracts develop rapidly between birth and 6 months. Consequently, we defined the duration of deprivation as the period extending from birth until the age at which the infant received contact lenses, following surgery to remove the cataract. Input from this point was only nearly normal because the contact lenses (or glasses, to which a few patients switched) focused input perfectly for only one distance and the eyes could not accommodate for other distances. (The implications of this continuing mild deprivation will be considered in the Discussion.) By school age, most patients began to wear bifocal glasses over the contact lenses to focus input at both a near and a far distance. Refractive error at the time of testing is shown in Table 1.

Normal control group

The control group consisted of 7 10-year-olds (+/– 3 months) and 10 adults (18–27 years). Ten-year-olds and adults did not differ significantly in accuracy on these tasks in our previous study (Geldart *et al.*, 1998), and

Table 1 *Clinical details of the 17 patients treated for bilateral congenital cataracts. Cases are in order of increasing deprivation*

Patient (Age-Yrs) (Sex)	Refraction* (diopters)	Days of deprivation	Snellen acuity*	Additional details
J.J. (14.5) (M)	OD +18.25 OS +15.75	53 53	20/60 20/30	Intermittent manifest nystagmus
A.H. (10.7) (F)	OD +16.25 OS +15.75	64 64	20/200 20/50	Microcornea OD; Manifest nystagmus; Strabismus surgery OD, age 1 year
K.M. (13.5) (F)	OD +12.50 OS +13.50	71 71	20/25 20/25	Glaucoma OU diagnosed age 13; Latent nystagmus OU
J.G. (12.0) (F)	OD +20.50 OS +23.75	83 83	20/60 20/60	Microcornea OU; Manifest nystagmus
C.B. (13.7) (F)	OD +17.75 OS +17.50	91 91	20/30 20/200	Latent nystagmus OS; Occasional latent nystagmus OD; Strabismus surgery for esotropia OS, age 2
T.S. (12.0) (M)	OD +12.50 OS +12.50	94 94	20/40 20/70	Glaucoma OU diagnosed age 9; Microcornea OU; Fine manifest nystagmus
A.D. (13.1) (M)	OD +17.50 OS +15.50	97 97	20/80 20/100	Latent nystagmus OU
A.R. (16.8) (F)	OD +17.00 OS +12.50	103 103	20/100 20/100	Microcornea OU; Manifest nystagmus; Strabismus surgery for esotropia OD, ages 1, 5 and 7
M.D. (17.3) (F)	OD +9.75 OS +9.00	129 129	20/30 20/60	Latent nystagmus OS
Z.C. (11.4) (M)	OD +14.50 OS +15.25	142 142	20/300 20/400	Glaucoma OS diagnosed age 4; Manifest nystagmus
A.C. (17.9) (M)	OD +11.25 OS +12.25	196 161	20/40 20/50	Manifest nystagmus
B.B. (11.1) (F)	OD +13.00 OS +14.50	165 165	20/70 20/70	Intermittent manifest nystagmus
C.P. (16.0) (M)	OD +10.25 OS +11.75	187 187	20/25 20/50	Latent nystagmus OU; Strabismus surgery for esotropia OS, age 2
T.C. (17.8) (F)	OD +18.50 OS +19.00	209 209	20/70 20/200	Glaucoma OS diagnosed age 4; Manifest nystagmus
S.S. (13.1) (M)	OD +12.75 OS +12.00	228 228	20/60 20/200	Manifest nystagmus
D.D. (38.4) (F)	– –	330 330	– –	Glaucoma OU; No medical records available
S.G. (22.0) (M)	OD +8.50 OS +9.75	586 586	20/100 20/100	Glaucoma OU diagnosed age 22; Manifest nystagmus

OD = right eye; OS = left eye; OU = both eyes.
*Values based on the measurement closest to the testing date.

so we used their combined scores as the normative group. For this study, we randomly chose the data from a subset of normals in the original study that allowed us to match them to patients in mean age (i.e. 16 years) and sex. None had a history of eye problems, and all met our criteria on a visual screening exam designed to detect any signs of previous abnormal visual experience: Snellen acuity of at least 20/20 in each eye without optical correction; worse acuity with a +3 diopter lens (to rule out farsightedness of greater than 3 diopters); binocular fusion at near on the Worth Four dot test; and stereoacuity of at least 40 arc s on the Titmus test.

Stimuli

A Chinon ES-3000 electronic still camera was used to create digitized images (grey scale, 256 × 256 pixels) of the faces of Caucasian adults, aged between 18 and 28 years. One flash unit was positioned behind the camera and faced a wall so as to diffuse the light and minimize shadows. Models wore a cape to cover clothing, wore a surgical cap over the hair and ears, and removed paraphernalia (e.g. glasses, earrings). Faces were photographed from 1 m, with a 3X zoom lens set so that each face measured 11 cm (6.3 visual degrees from 100 cm) from the top of the forehead to the bottom of the chin.

We used Adobe Photoshop to remove natural markings (e.g. freckles, moles), to center the images, and to crop them to a size of 10 cm wide and 15 cm high (5.7° by 8.6° from 100 cm). The faces were large enough so that their features would be visible to patients who have reduced visual acuity and contrast sensitivity. Studies of a similar cohort indicate that 95% can detect a stripe that is at least 10 minutes of arc wide (Maurer & Lewis, 1993) and that has a contrast of at least 10% (Tytla, Maurer, Lewis & Brent, 1988). Therefore, we made the widths of the sclera and iris well above 10 minutes wide (i.e. 20 minutes of arc), and we increased the contrast in light-colored faces so that the contrast between the iris and sclera, the lips and the chin, and the nose and cheek, was at least 10% (mean: 28%; range: 11 to 38%).

Apparatus and procedure

After the procedures were explained, we obtained written consent from participants over 15 years of age and from parents of younger children; we also obtained assent from children 15 years of age and younger. Before computerized testing, each normal participant completed the visual screening test (see Participants). When necessary, the patient wore a trial frame with lens(es) having additional optical correction so that both eyes were focused at the testing distance of 100 cm.

Stimuli were presented on a 21″ monochrome Radius 21-GS monitor. The experiment was controlled by Cedrus Superlab software and a Macintosh LC 475 computer. A joystick, held by the subject to make responses, was connected to the computer via a keyboard. The keyboard was placed in front of the tester, who used it to initiate each trial.

There were six test trials for each of five tasks and a training task. Each trial contained four faces of the same sex. With the exception of the training task, those four faces were matched closely on external contour, complexion and color of eyes and eyebrows. On each trial, a target face appeared at the top of the computer screen for 2 seconds, and following an interstimulus interval of 396 ms, three test faces, which were the same size as the target face, appeared side-by-side at the bottom of the screen. The test stimuli were presented after the target disappeared in order to prevent subjects from analytically comparing the features of the target and choice stimuli, but the interstimulus interval was kept brief to minimize memory demands. For three of the tasks (1, 3, 4) the participant was instructed to indicate which of the three test faces matched the target face by moving the joystick either to the left, to the right or forward (if the matching face was in the middle). However, during pilot work, adults made errors on tasks 2 and 5 by moving the joystick toward the direction in which the matching face was oriented rather than its location on the screen. Therefore, only for tasks 2 and 5 were participants asked to indicate the location of the matching face verbally or by pointing, rather than by using the joystick, and the tester coded their choices. The tester emphasized accuracy but asked the subject to respond as quickly as possible. The test faces disappeared once a response was made.

All tasks, including the training task, began with three practice trials. For each task, half of the six test trials used male faces and half female faces, and there was at least one trial in which the matching face was positioned on the left, middle and right of the screen. We did not counterbalance the location of the matching face across the six trials of each task because we did not want subjects to be able to guess the correct location for the last one or two trials. Instead, we counterbalanced the correct location across all 36 trials that made up the six tasks (training + 5 tasks). In addition, we created a second version of each task that differed in the number of correct responses in the left, middle and the right, but otherwise followed the same constraints, and then randomly assigned participants to one of the two versions of each task.

The tasks are described in the order in which they were presented, which was the same for all participants and based on the order which normal controls found easiest during pilot work. Pilot subjects reported it easier to understand the instructions for matching when the identity tasks came first. The procedure began with a training task of the same type. There were too few patients to counterbalance the order of presentation of the tasks. Instead, we assumed that any effect of order – caused by practice and/or fatigue – was comparable across patients and normal controls. Subjects did not receive feedback, except for the first practice trial of each task.

Training task

The training task used faces facing forward (i.e. frontal) with a neutral facial expression. The subject was asked to choose the test face that matched the target in identity. The training task was easier than the experimental tasks because, unlike the experimental tasks, one of the test faces was a duplicate of the target face, some of the faces had unique markings (e.g. moles, freckles), and the faces were not matched on chin contours, complexion or coloring of eyes and eyebrows. Any subject who failed the criterion of at least 5/6 correct was allowed to repeat the training task up to three times, in each case with a different version that re-positioned the correct matching face. Most patients and normal subjects reached the criterion in the first attempt. One patient (Z.C.) did not pass the training task until the third attempt.

Task 1: Identity/changed facial expression

Task 1 used faces posing with their head and eyes frontal and with one of four emotional expressions: neutral, surprise, happy, disgust. Each trial used all four expressions: the target face had one facial expression (e.g. happy) and was followed by the same person's face but with a different facial expression (e.g. neutral) and two novel faces, with the two remaining expressions. The subject was asked to use the joystick to indicate which test face had the same identity as the target despite changed facial expression.

Task 2: Identity/changed head orientation

Task 2 used faces posing with a neutral facial expression and with their head and eyes frontal, 45° to the right, 45° to the left, 45° up or down. Each trial used four head orientations: the target face posed with one head orientation (e.g. right), and was followed by the same face but with a different head orientation (e.g. left) and two novel faces, posing with two remaining head orientations (e.g. down, up). The subject was asked to choose, by pointing, the test face with the same identity as the target despite changed head orientation.

Task 3: Facial expression

Task 3 used faces posing with their head and eyes frontal and with one of four emotional expressions: neutral, surprise, happy, disgust. Each trial had three possible facial expressions: the target face with one expression (e.g. surprise) was followed by one novel face posing with the same expression (i.e. surprise) and two novel faces, each with different expressions. The subject was asked to use the joystick to indicate which test face had the same facial expression as the target.

Task 4: Lip reading

Task 4 used faces posing with their head and eyes frontal and pronouncing one of three long vowels: a, e, u. Each trial used all three vowels: the target face mouthing one vowel (e.g. u), was followed by one novel face mouthing the same vowel, and two novel faces mouthing the two remaining vowels. The subject was asked to use the joystick to indicate which test face was mouthing the same vowel as the target.

Task 5: Direction of gaze

Task 5 used faces posing with a neutral expression, in one of six possible combinations of gaze and head orientations: eyes and head frontal; eyes and head 30° to the left (or right) of the camera; eyes frontal and head 30° to the left; eyes 30° to the right (or left) and head frontal. Each trial contained four types of gaze/head direction: the target face posed with one gaze direction and head orientation (e.g. eyes 30° left; head frontal), and was followed by one novel face with the same gaze direction as the target (i.e. 30° left) but a different head orientation (e.g. 30° left), and two novel faces with a different gaze direction from the target and the same or different head orientation as the target (e.g. frontal, 30° right). The subject was asked to choose, by pointing, the test face having the same direction of gaze as the target, and to ignore any changes in the direction of the head.

Results

We used separate 2-way ANOVAs, each with one between-subjects factor (group) and one within-subjects factor (tasks), to analyze the effect of early visual deprivation on accuracy and reaction time on correct trials. For analyses of accuracy, data from all five tasks were included. For analyses of reaction time, data were available from only the three tasks for which participants coded their own responses using the joystick: identity/changed facial expression, facial expression and lip reading. To reduce the effect of trials with outlying values, we calculated the median reaction time for each participant, during each of the three tasks.

Figure 1 shows the mean accuracy score for the normal control group for each of the five tasks, and the accuracy score for each patient plotted as a function of the duration of the patient's visual deprivation. The ANOVA on accuracy revealed main effects of group ($F(1, 32) = 10.34$, $p < 0.01$) and task ($F(1, 4) = 44.89$, $p < 0.001$) and an interaction between group and task ($F(1, 128) = 3.94$, $p < 0.01$). Patients were as accurate as normal controls on the tasks that required matching faces based on facial expression, lip reading and direction of gaze (analyses of simple effects, all ps > 0.10). Patients performed worse than normal controls in matching faces' identity/changed head orientation ($p < 0.001$), and they tended to perform worse in matching faces' identity/changed facial expression ($p = 0.067$). The main effect of task reflects the fact that both groups made more errors on the two identity tasks than on the other tasks (Tukey ps < 0.05).

There was no significant relationship between patients' accuracy on any task and the duration of their visual deprivation (range of rs $= 0.10$ to 0.35, all ps > 0.10) or the Snellen acuity in their better eye (range of rs $= 0.09$ to 0.45, all ps > 0.05). In particular (see Figure 1), there

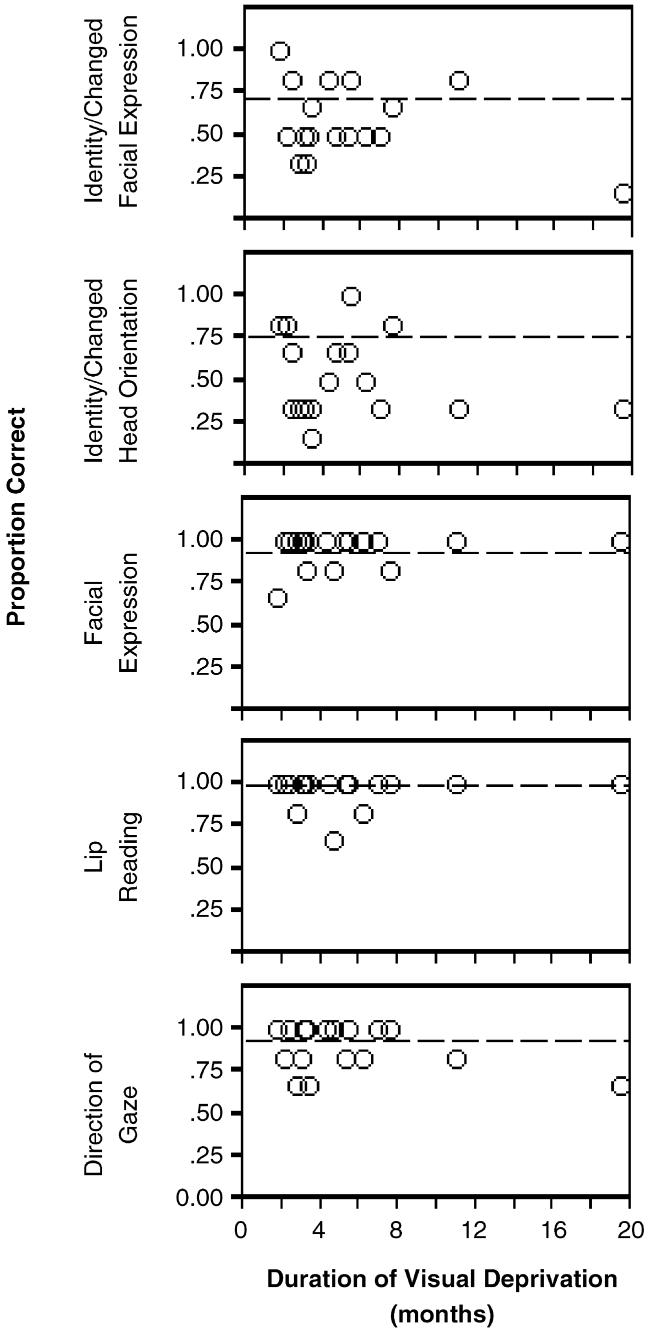

Figure 1 *Accuracy scores for five tasks of face matching in patients with a history of early visual deprivation. Each dot represents accuracy for one patient plotted as a function of the duration of visual deprivation. For comparison, the mean accuracy from normal controls for each task is illustrated by a dotted line. Points on or near the line are within normal limits; points well below the line represent deficits. Chance performance is 0.33.*

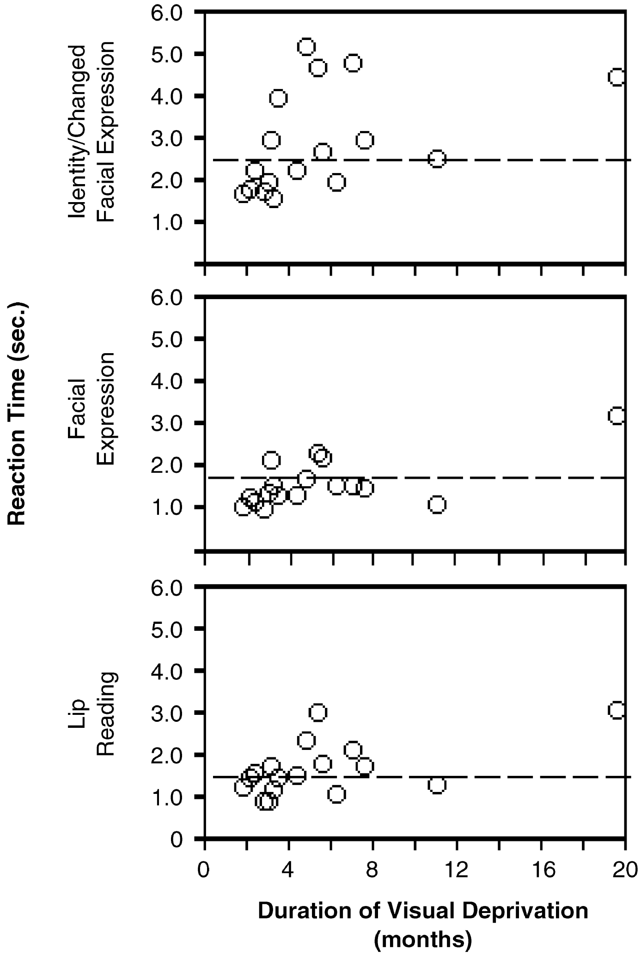

Figure 2 *Median reaction times for three tasks of face matching in patients with a history of early visual deprivation, plotted as a function of the duration of each patient's visual deprivation. The mean reaction time from the norm group for each task is shown by a dotted line. Other details as in Figure 1.*

was no obvious effect of the duration of visual deprivation on patients' deficit in matching faces' identity/changed head orientation.

Figure 2 shows the median reaction time for each patient (and the normal mean) for matching faces based on identity/changed facial expression, facial expression and lip reading. The ANOVA of reaction times revealed an interaction between group and task ($F(2, 64) = 23.625$, $p < 0.05$), and a main effect of task ($F(2, 32) = 41.123$, $p < 0.001$). Inspection of Figure 2 suggests that patients differed from normal controls on matching identity/changed facial expression, but analyses of simple effects showed that patients did not differ from normal controls on any of the tasks (all ps > 0.05). Moreover, removal of the patient (Z.C.) with the poorest visual acuity and the patient (D.D.) for whom acuity values were unavailable, eliminated the significant interaction of group and task for reaction time ($p > 0.05$) but preserved the significant interaction for accuracy ($p < 0.01$). The significant effect of task reflected the fact that both patients and normals were just as fast on the task of matching facial expression as on the task of lip reading (Tukey $p > 0.05$), and were significantly faster on both of those tasks than on the task of matching faces' identity with changed facial expression (both ps < 0.01).

There was no significant relationship between patients' Snellen acuity in their better eye and their reaction times on the two tasks that required matching facial expression and lip reading (rs $= 0.29$ and 0.42, respectively, ps > 0.10). There was a significant relationship between acuity and reaction time in matching identity/changed facial expression ($r = 0.62$, $p < 0.05$), but that relationship was produced by the patient with the poorest vision (Z.C.), and no longer reached statistical significance when his score was removed from the analysis, $r = 0.46$, $p > 0.05$. The relationship between patients' median reaction times and the duration of their visual deprivation was significant for the tasks of matching facial expression and lip reading (rs $= 0.65$ and 0.57, respectively, ps < 0.05), but not for the task of matching identity/changed facial expression ($r = 0.43$, $p > 0.05$). However, the significant correlations were produced by the patient with the longest deprivation (S.G.; 586 days, see Table 1) and no longer reached significance when his score was removed from the analyses (rs $= 0.13$ and 0.22, respectively, ps > 0.10).

Discussion

This was the first study of the effect of early visual deprivation on the development of face processing, and indicates that visual input in the weeks immediately after birth is necessary for some, but not all, aspects of face processing. Specifically, patients with a history of early visual deprivation performed abnormally on the task that required matching faces' identity despite changes in head orientation. On that task, patients' mean accuracy was above chance (33%), but more than 20% lower than that of normal controls (53% vs. 75%, Figure 1). Patients also tended to be less accurate than normal in matching faces' identity despite changed facial expression. Patients' reaction times did not differ from those of normals, so their poor accuracy scores cannot be attributed to speed/accuracy tradeoffs. Thus, like early insult to the brain (Gepner *et al.*, 1996; Mancini *et al.*, 1994), early visual deprivation causes long-term deficits in the ability to process some aspects of faces, even after many years of viewing human faces after treatment. The results add support to theories arguing for independent cortical systems involved in face processing (Bruce & Young, 1986) – only some of which appear to depend on early visual experience.

Visual deprivation as short as 2 months was sufficient to prevent the normal processing of facial identity, despite the fact that normal development continues until at least 10 years of age (e.g. Carey, 1981, 1992; Flin, 1980; Geldart *et al.*, 1998). During those first months of rapid cortical development (e.g. Bronson, 1974), infants receive a wealth of experience with faces and a number of face-processing skills emerge (e.g. recognizing faces based on internal features, discriminating facial expressions and gaze directions) (Barrera & Maurer, 1981; de Schonen & Mathivet, 1990; Vecera & Johnson, 1995). Our results are consistent with the hypothesis that early visual experience is critical for setting up the cortical architecture that will become specialized for face processing over the next 10 years (de Schonen & Mathivet, 1989; Johnson & Morton, 1991). That architecture might involve what Johnson and Morton call Conlern – a cortical mechanism that learns about faces and their identity. As well, it may involve the circuitry in the right hemisphere that de Schonen (de Schonen & Mathivet, 1989) argues becomes specialized for configural processing as a result of newborns' bias to encode primarily large features and the spatial relationships among them. When Conlern develops in the absence of biased input with faces during infancy – as was the case for our patients – it may not be able to learn subsequently about facial identity in a normal way. One reason may be that delaying visual input to the right hemisphere permanently alters its sensitivity to low spatial frequencies and, consequently, its specialization for configural processing of objects that were experienced early in development. Apparently, delayed visual input was enough to allow the normal development of other face processing skills – processing facial expressions, direction of gaze and vowel being mouthed – at least as measured by our tasks.

Our tests were not designed to assess the strategies used for matching, and therefore we cannot be certain of the nature of patients' deficits or whether they are limited to certain aspects of face processing. It is possible that differential task difficulty contributed to the pattern of deficits, with larger deficits on the tasks that were harder for normal subjects (i.e. the two identity tasks) and smaller deficits on the easier tasks, the sensitivity of which may have been limited by a ceiling effect. Both accuracy and reaction times indicated that the tasks that required lip reading and matching emotional expression were easier for both patients and normal controls than the task that required matching identity across emotional expressions. (Comparisons with the other tasks were not possible because reaction times were not collected.) Patients may be poor in recognizing expressions of emotion or lip reading when expressions change subtly or quickly in face-to-face interactions. They may also be poor at recognizing non-face objects across different points of view. Nevertheless, the overall pattern of results suggests that early visual deprivation spares the development of the processing of local features. Patients appeared to be as proficient as normal individuals in processing small, individual features (the shape of the lips) or local relations (the direction of gaze), but failed tasks that could not be solved on that basis (recognizing identity when the shape of individual features changes with head orientation or facial expression). A subsequent study confirmed the hypothesis that patients treated for bilateral congenital cataract are normal at processing facial features but have a deficit in processing the spacing among those features, i.e. configural processing (Le Grand, Mondloch, Maurer & Brent, 2001). They are also normal at noticing changes in the spacing of an internal element inside a geometric pattern (Geldart, 2000), a non-face task which requires configural processing and which is particularly difficult for normal 6-year-olds (Geldart, 2000). Collectively, the data suggest that early visual input is especially important for setting up the neural architecture that will become specialized for the configural processing of faces.

A second alternative explanation is that patients performed poorly because the poor visual acuity caused by the deprivation (see Table 1) prevented them from seeing the stimuli clearly. This alternative seems unlikely because: (1) facial features were made large and with enough contrast to compensate for patients' poor vision (see Methods); (2) patients performed normally in matching direction of gaze, and hence, were able to resolve the small details in the eye features well enough to find the correct match; and (3) there was no significant correlation between acuity and accuracy for any of the tasks. Other problems, such as nystagmus and strabismus, might have degraded the facial images, but there was no relationship between the presence of these conditions and performance. Moreover, patients viewed the stimuli binocularly, and hence, with the dominant or fixating eye in use.

A third alternative interpretation is that the patients' abnormalities were caused by abnormalities in visual input after treatment of the cataracts. Because surgery involved removing the natural lens, the contact lens fit after treatment focused input to each retina perfectly for only one distance, until school age when it was supplemented by bifocal glasses. However, the fixed focus is unlikely to have compromised facial input. The power of the patient's contact lenses was chosen to focus visual input at arm's length during infancy – the distance for normal face-to-face-interaction between the infant and adult. After infancy, it was usual to leave one eye focused for near objects, and thus, to receive normally focused input from faces. It is also unlikely that the abnormalities arose from growing up with poor acuity, and hence, compromised visual input, at least for the period from treatment until about 18 months of age. Immediately after treatment, patients' visual acuity is more similar to that of newborns than that of age mates (Maurer, Lewis, Brent & Levin, 1999), but then improves faster than normal so that by 1 year of age it is within normal limits (Lewis, Maurer & Brent, 1995; reviewed in Maurer & Lewis, 2001). Thus, over the first year following treatment, the visual system of patients received the same range of spatial frequencies as normal infants. Of course, visual input may be compromised in other ways or at later ages, either because of the onset of associated ocular conditions (e.g. strabismus) or because visual acuity fails to improve at a normal rate after age 2 (Lewis *et al.*, 1995). Nevertheless, patients have had years of experience viewing human faces binocularly – with their better eye available. Furthermore, growing up with reduced acuity and poor contrast sensitivity (Ellemberg, Lewis, Liu, Maurer & Brent, 1999; Tytla *et al.*, 1988) would compromise input necessary to see small facial details, but not the low spatial frequencies specifying the spacing among features. Such visual input biased toward low spatial frequencies after infancy should in turn promote proficiency in configural processing but cause deficits in the processing of local features – a pattern opposite to that observed in this study. Taken together, the evidence suggests that patients' deficits were caused by early visual deprivation rather than by later deviations from normal input or poor vision during testing.

In summary, our findings suggest that early visual experience is critical for the emergence of expertise in processing facial identity, perhaps because it establishes the neural circuitry that will become specialized for expert configural processing of faces. Future research with tasks designed to separate the processing of local features, their spacing and the external contour in a variety of objects is needed to determine whether the deficits are restricted to faces or extend to the recognition of any object across different points of view. In any case, the results complement previous studies that have revealed an adverse effect of early visual deprivation on the development of aspects of sensory vision that are immature at birth and that develop postnatally (e.g. Maurer *et al.*, 1989). Taken together, the findings suggest an important role for early visual experience in the development both of sensory vision and of higher-level function such as face processing.

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