Research report

Failure in developing high-level visual functions after occipitoparietal lesions at an early age: A case study

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ABSTRACT

Previous functional magnetic resonance imaging (fMRI) studies have identified several regions in the ventral visual pathway that are specialized for processing faces, words and general objects. However, little is known about the origin of the functional selectivity of these regions. Here, we reported a pediatric patient who suffered a left occipitoparietal lesion in the first year after birth from a subdural hematoma. After the hematoma was removed at the age of six, the hemianopia in the right visual field was alleviated, and no obvious deficits in low-level vision were observed in the patient at the age of twelve. In line with the behavioral observations, meridian mappings with fMRI showed that the early visual cortex of the left hemisphere was significantly activated, which was similar to that of the intact right hemisphere. However, the left ventral temporal cortex failed to show selective responses for faces, words and objects, which were in contrast to the normal selective responses for these objects in the right counterpart. Therefore, it is likely that the development of object selectivity in the ventral temporal cortex depends on visual inputs from the early visual cortex at an early age.

1. Introduction

Previous functional magnetic resonance imaging (fMRI) studies have identified multiple functionally specialized regions in the ventral visual pathway that respond selectively to particular object categories (e.g., faces, words and general objects) (Cohen et al., 2000; Grill-Spector et al., 1999; Kanwisher, McDermott, & Chun, 1997). Although adult-like object-selective responses are observed in children as early as the age of five (Golarai et al., 2007; Scherf, Behrmann, Humphreys, & Luna, 2007), only until adolescence does the object selectivity reach the adult level (Aylward et al., 2005; Brem et al., 2006; Gathers, Bhatt, Corbly, Farley, & Joseph, 2004; Golarai et al., 2007; Nishimura, Scherf, & Behrmann, 2009; Passarotti et al., 2003; Robbins, Shergill, Maurer, & Lewis, 2011; Scherf et al., 2007). During development, the size of the object-selective regions is expanded (Aylward et al., 2005; Golarai et al., 2007; Scherf et al., 2007), and the selectivity is
increased (Pascalis, de Haan, & Nelson, 2002; Peelen, Glaser, Vuilleumier, & Eliez, 2009; Scherf et al., 2007). Even in adults, the visual cortex is still malleable, and short-term visual experiences are able to shape the functionality of these regions (Kourtzi & DiCarlo, 2006; Op de Beeck & Baker, 2010; Song, Bu, Hu, Luo, & Liu, 2010; Song, Hu, Li, & Liu, 2010; Song, Tian, & Liu, 2012). These findings together suggest the important role of continuous visual experiences in the development of the functional selectivity of object-selective regions in the ventral pathway (Johnson, 2001; Lewis & Maurer, 2009). However, little is known about how critical visual experiences are in shaping the high-level visual cortex during development. Here, we reported a case in which a pediatric patient had experienced hemianopia in the right visual field since the first year after the birth and then recovered after surgery was performed when the patient was six. We examined whether the functional selectivity in the left temporal cortex developed properly in the absence of visual inputs at an early age.

Studies of visual deprivation and lesions have provided ample evidence for the critical role of visual inputs in functional development. The pioneering work of Hubel and Wiesel (1963, 1965) of testing visually deprived cats has shown that visual inputs are critical for the development of binocular vision. Studies have shown that high-level visual functions that develop later are more likely to be affected by visual experience (Daw, 2003; see also Lewis & Maurer, 2009) compared to low-level visual functions that usually develop at early ages (Caird, Gillespie, & Stryker, 1998; Horton & Hocking, 1996; Rathjen & Lowel, 2000). Bova et al. (2008) have described a pediatric patient who had an infarction of the bilateral occipital lobe at the age of two years and six months. After four years’ recovery, most low-level visual functions had improved significantly, except for object recognition in a complex environment. Similar findings have been observed in studies of children with congenital or early-age cataracts. After surgical removal of the defective natural lenses of the eyes, visual inputs are largely restored, but patients are severely impaired in processing global form (Ellemberg, Lewis, Maurer, Brar, & Brent, 2002; Lewis et al., 2002), global motion (Ellemberg et al., 2005; and see Hadad, Maurer, & Lewis, 2012), and face configuration (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002; Le Grand, Mondloch, Maurer, & Brent, 2001, Le Grand, Mondloch, Maurer, & Brent, 2003). Even several years after their surgeries, the patients are still unable to process faces holistically (Le Grand, Mondloch, Maurer, & Brent, 2004; Mondloch, Le Grand & Maurer, 2003; Robbins, Maurer, Hatry, Anzuere, & Mondloch, 2012).

The aforementioned behavioral studies have clearly demonstrated that the development of high-level visual functions, especially object recognition, requires visual inputs at an early age. However, it is unclear how the ventral visual cortex is affected by the disruption of visual inputs at an early age. In order to address this question, we used fMRI to investigate a pediatric patient (CGN) with right homonymous hemianopia from a subdural hematoma in the left occipitoparietal cortex that was observed when CGN was one year old. At the age of twelve years eight months, or six years and one month after the surgery, his low-level vision seemed to be fully recovered. To quantify the visual functions of the visual cortex, we first performed meridian mapping in order to examine whether the functionality of the early visual cortex was properly recovered. Then and more critically, we presented a variety of objects, including faces, words and objects, to the patient in order to characterize object-selective responses in the ventral pathway. If visual inputs at an early age are critical to the development of object-selective regions, we expected to observe underdeveloped selectivity to objects in the left ventral visual pathway. If not, after the visual inputs were restored after the surgery, we expected to observe normal or near normal selectivity for objects in the ventral pathway.

2. Materials and methods

2.1. Case description

CGN is a left-handed male child. He was born at term after a normal pregnancy and uneventful labor. He was diagnosed with encephalitis one and a half months after birth and was hospitalized for one month. After he was one year old, his right extremities started to involuntarily twitch. This symptom occasionally expanded to his left extremities.

When he was six years and seven months old, he participated in his first MRI scan at the First Affiliated Hospital of Jinan University, Guangzhou, China. The T1-weighted images revealed a subdural hematoma and underdeveloped occipitoparietal cortex in the left hemisphere. The hematoma was located between the left superior parietal lobe and the skull, and it caused significant atrophy around the left temporal–parietal–occipital junction (Fig. 1A). T2-weighted images showed abnormal hyperintense areas in the superior parietal lobe, precuneus, cuneus, intraparietal sulcus, and part of the superior temporal gyrus (Fig. 1B).

Besides the MRI scan, CGN participated in behavioral tests to examine his visual perception, including the rapid object naming test, clinical confrontation test, spontaneous painting test, and line bisection test (Barton & Black, 1998). In the rapid object naming test, a black fixation cross was first presented at the center of the visual field on a white background, and CGN was instructed to fixate on the cross. Then, a familiar object (e.g., car, frog or hat) was presented for 200 msec in one of nine squares that were evenly distributed in a 3 × 3 matrix, and CGN was asked to name the object (Fig. 1D). The size of a square was 4.6° × 3.4°, and the whole nine squares covered 13.7° × 10.3° of the visual field. In Fig. 1D, the objects that CGN named correctly are marked in white, and those he failed are marked in gray. In the first trial, CGN correctly named the objects that were located in the lower left and upper center of the visual field. In the second trial, CGN correctly named the objects that were located in the upper left, lower left, and center. That is, CGN was only able to name objects that were shown in the left visual field in the rapid object naming test. In the spontaneous painting test, the picture was left centered with relatively complete left and right structures (Fig. 1C). In the line bisection test, CGN was instructed to estimate and mark the midpoint of various oriented lines that were shown on paper. He started from the upper left part of the paper and then completed all of the marking lines on the paper. All of the marks that he drew were at the center of the lines. These three
tests together suggested that CGN suffered right homonymous hemianopia without hemispatial neglect. The clinical confrontation test confirmed the diagnosis (Johnson & Baloh, 1991; Shahinfar, Johnson, & Madsen, 1995).

A craniotomy was performed one day later, and the subdural hematoma was removed successfully. Two perimeter tests were conducted after the surgery with a QZS-III autoperimeter from Beijing Aerospace Institute for Metrology and Measurement Technology (radius of the half ball screen, 300 mm; background illumination, 4 asb; illumination of stimulus spots, 2.5 to 1000 asb; diameter of the stimulus spot, 2 mm; and range of examination, 30° for the central visual field and 30° to 60° for the peripheral visual field). The first perimeter test was conducted three years after the surgery, and CGN showed normal visual fields, except for a relatively low light sensitivity in the peripheral visual field of the right eye's nasal side and in the central visual field of the right eye's upper side. The second perimeter test was conducted five years and three months after the surgery, and no significant deficits in the visual field were found (Fig. 2B). Therefore, after the surgery, CGN's hemianopia was greatly alleviated with visual inputs from the right visual field to the left hemisphere being restored.

Consistent with the behavioral testing, CGN also reported the improvement in everyday visual functions during medical examinations after the surgery. At the age of nine years and eight months (three years and one month after the surgery), CGN reported visual hallucination of ghost images, which occurred six to seven times per day. At the age of ten, CGN reported that the visual hallucination became rare; instead, he frequently saw black shadow in the right visual field that corresponds to the impaired hemisphere. Two months later, he reported that the shadow only occurred occasionally. At the age of eleven years and three months, CGN reported that the black shadow became black dots, which occurred very rare in the right visual field. At the age of eleven years and four months (four years and nine months after the surgery), CGN reported neither visual hallucination nor black shadow. At the time of the fMRI scan, CGN reported no difficulties about everyday visual functions either in school or at home, which was confirmed by his mother. Similarly, from the visual inspection before the fMRI scan, we did not observe any obvious abnormality of his right visual field during visual contact, or when he played toys and carried out the practice trials of fMRI experiments out of the scanner. Therefore, because of limited testing time, we did not use behavioral tasks to further examine CGN's behavioral performance in peripheral vision or his low-level visual functions (e.g., sensitivity for spatial frequencies).

Fig. 1 – Preoperative tests. A) Preoperative T1-weighted scan showing that the subdural hematoma was located between the left superior parietal lobe and the skull, and it caused significant atrophy in the left occipitoparietal cortex. B) Preoperative T2-weighted scan showing hyperintensity in regions from the left superior parietal lobe to the left temporal lobe. C) In a spontaneous painting by the subject (CGN), the structure was slightly left centered. D) Rapid object naming test. Pictures of nine objects were presented serially on the screen. The objects that CGN named correctly are marked with a white background, whereas those he failed to name are marked with a gray background. (In the experiment, the background was always white, and the gray background was used only for display purposes.) In general, he could only name the objects that were shown on the left side.
2.2. Experimental procedure

We scanned CGN at the age of twelve years and eight months, or six years and one month after the surgery to examine the development of the object-selective regions in his left hemisphere. One structural MRI scan and two functional MRI scans were conducted. The T1-weighted structural scan was designated to examine the location of the brain lesion after the surgery, and the fMRI scans aimed to test the functionality of the early visual cortex (i.e., the meridian mapping) and the object selectivity of the ventral pathway. The scan was performed on a Siemens 3T Trio scanner (Magnetom Trio, A Tim System, Siemens Medical Solutions, Erlangen, Germany) with a 12-channel phased-array head coil at BNU imaging Center for Brain Research, Beijing Normal University, Beijing, China. The MRI protocol was approved by the institutional review board of Beijing Normal University. Informed consent was obtained from CGN’s parent before his participation.

2.2.1. Structural MRI scan

MPRAGE, an inversion prepared gradient-echo sequence (bandwidth, 190 Hz/pixel; flip angle, 7°; repetition time (TR)/Echo time (TE)/inversion time (TI), 2.53 sec/3.45 msec/1.1 sec; voxel size, 1 × 1 × 1 mm³), was used to acquire 3-dimensional structural images. Structural images were processed with the automatic structural imaging stream in FreeSurfer (http://surfer.nmr.mgh.harvard.edu/). The inflated surface of the cerebral cortex was generated to display neural activations.

2.2.2. Meridian mapping

A 22.5° sector of a circular checkerboard pattern was used to functionally map the visual field of the early visual cortex. The radius of the circular checkerboard subtended a visual angle of approximately 6.1°. The checkerboard sector was presented in one of four quadrants of the visual field (i.e., upper, lower, left and right) in a blocked-design fashion. The total scan lasted 336 sec, and it consisted of four groups of four consecutive 16-sec blocks, one for each quadrant, that was presented in a counterbalanced order. Each group of blocks was preceded and followed by a 16-sec baseline fixation block. In addition, a fixation ring was presented at the center of the screen, and CGN was instructed to press a button when the illumination of the ring was changed. There were four scans for the meridian mapping.

2.2.3. Functional selectivity for objects

Four object categories, which consisted of 16 exemplars of faces, words, familiar objects and scrambled objects, were used to examine the object selectivity in the ventral visual cortex (Fig. 3A). All stimuli were gray-scale photographs that subtended a visual angle of approximately 7.3° × 7.3°. Face photographs were from an in-house Chinese face databank,
words were frequently used Chinese characters, and objects were daily objects (e.g., banana, umbrella). CGN reported that he was familiar with both the words and the objects used in the test. Scrambled objects were created by dividing the objects into 400 squared pieces and then randomizing the locations of the squares. The scan procedure was similar to the meridian mapping, except that the stimuli were faces, words, familiar objects and scrambled objects that were presented in the center of the visual field. In addition, each image was presented for 1000 msec within a block. CGN was instructed to press a button when two consecutive images were identical (i.e., one-back task). The repetition of images occurred twice per block. There were four scans for examining the object selectivity of the visual cortex.

2.2.4. fMRI data acquisition and analysis
Twenty-five 4-mm thick (20% skip) axial slices were collected (in-plane resolution, 3.1 × 3.1 mm²), which covered the entire brain. T2-weighted, gradient-echo, and echo-planar imaging procedures (EPI) were used (TR, 1.5 sec; TE, 30 msec; flip angle, 90°). Functional data were analyzed with FS-FAST (FreeSurfer functional analysis stream, CorTechs Labs Inc., La Jolla, CA, USA) (Dale, Fischl, & Sereno, 1999; Fischl, Sereno, & Dale, 1999). After data preprocessing, which included motion correction, intensity normalization, and spatial smoothing (Gaussian kernel, 6 mm full width at half maximum), the voxel time courses were fitted with a general linear model. Each condition was modeled by a boxcar regressor that matched its time course, which was then convolved with a gamma function (delta, 2.25; tau, 1.25). For the meridian mapping, the neural responses for the checkerboard sectors were calculated by contrasting the responses to each checkerboard sector compared to that with fixation (p < .05, uncorrected). In the functional selectivity experiment, there were three types of measures. The first measure was to examine the neural activation for any form of visual stimuli in the ventral visual pathway by contrasting the responses for all visual stimuli (faces, words, objects and scrambled objects) with those for fixation (p < .01, uncorrected). The second measure was to examine the processing of general object
shapes, which contrasted all objects (faces, words and objects) with scrambled objects ($p < .05$, uncorrected). Finally, we defined regions that responded selectively for each object category respectively ($p < .05$, uncorrected). That is, face-selective regions (fusiform face area – FFA; face-selective superior temporal sulcus – STS) (Hoffman & Haxby, 2000; Kanwisher et al., 1997; Liu, Harris, & Kanwisher, 2010) were defined by the contrast of faces versus objects; object-selective regions (lateral occipital cortex – LO; posterior fusiform gyrus – pF) (Grill-Spector et al., 1999) were defined by the contrast of objects versus scrambled objects; and the word-selective regions (visual word form area – VWFA; inferior frontal gyrus – IFG) (Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003; Song, Bu, et al., 2010, Song, Hu, et al., 2010) were defined by the contrast of words versus objects. To further test whether the selectivity for faces and objects in CGN’s face- and object-selective regions in the intact right hemisphere was in the normal range, we used effect size (Cohen’s $d$) as an index for the level of the selectivity. Specifically, we first generated a $3 \times 3 \times 3$ cubic-shaped voxel cluster around the peak voxel within each pre-defined region as a region of interest (ROI), and then calculated the effect size of the selectivity of the ROI. The reason to limit the number of voxels in an ROI rather than to select all voxels within a region was to keep the signal-noise ratio consistent across ROIs while averaging.

To explore the relation between neural activation and object selectivity, an analysis of variance (ANOVA) was performed with factors being hemisphere (left vs right) and activation versus selectivity. To do this, we first defined ROIs in the early visual cortex (i.e., V1) and high-level visual cortex (i.e., inferior temporal cortex) of both hemispheres. Specifically, we localized the most activated voxels with the contrast of visual stimuli (faces, words, objects and scrambled objects) versus fixation in the V1 and in the inferior temporal cortex of both hemispheres respectively, and then created a $4 \times 4 \times 4$ cubic-shaped voxel cluster around each pre-defined voxel as an ROI. Second, the activation was defined as the magnitude of neural responses of the V1 ROIs for checkerboard sectors versus fixation (left sectors for the right V1 ROI, and right sectors for the left V1 ROI) in the meridian mapping experiment. The selectivity was defined as the magnitude of selective responses of the ROIs in the inferior temporal cortex for general object shapes (faces, words and objects) versus scrambled objects. The values of effect size (Cohen’s $d$) per condition per voxel were submitted to the ANOVA analysis.

2.3. Typically-developing children (TDC)

Six age- and sex-matched children (male, age: 12.1 ± 3, ranging from 11.8 to 12.4) were recruited from primary schools in Beijing, China. They reported no past or current psychiatric illness or history of neurological disorders (e.g., epilepsy, traumatic brain injury, neurodegenerative disorders and cerebro-vascular disease), mental retardation or significant systemic medical illness. They all had normal or corrected-to-normal vision. Informed consent was obtained from the participants’ parents before their participation.

The functional selectivity experiment was conducted in the TDC to provide an overview of the normal development of object selectivity in the high-level visual cortex at the age of twelve when CGN was scanned. The experiment paradigm and data analysis were the same as those in CGN’s study, except that we replaced words with scenes for a purpose unrelated to this study. Therefore, in following analyses we focused on the selective responses for faces and objects in the TDC, which have been most studied previously. Besides, we did not conduct the meridian mapping experiment in the TDC because the question of interest was whether the object selectivity in CGN’s right hemisphere was in the normal range.

3. Results

At the time of this study, CGN was aged twelve years and eight months, or six years and one month after the surgery. We determined from our examination that his visual performance, including fixation, saccades and smooth pursuit, was generally normal. His reading and writing skills were appropriate for his age. When he played with a Transformers toy, his hand-eye coordination and fine hand motions were normal. To examine low-level and high-level visual functions of his ventral visual pathway, we first conducted a T1-weighted scan to investigate the structural lesion and then conducted two functional scans.

The structural MRI images showed a surgical lesion in the left occipitoparietal cortex at the location of the former hematoma, and severe atrophy in the left occipitoparietal cortex and, to a lesser extent, the temporal cortex. The main regions of atrophy included the superior parietal lobe, precuneus, cuneus, intraparietal sulcus, occipital lobe and the superior temporal gyrus. The frontal cortex in the left hemisphere was relatively intact. The right posterior occipital lobe was expanded towards the left side. The posterior horn of the left ventricle was enlarged towards the damaged site (Fig. 2A).

The meridian mapping showed significant neural activations in the early visual cortex, except for in the upper left portion of the occipital cortex. The checkerboard sector was shown at each of the four quadrants, which is able to elicit neural activation in the contralateral visual cortex in normal individuals (Wandell, Dumoulin, & Brewer, 2007). Similarly, the checkerboard sectors presented in the left and right quadrants predominantly activated CGN’s contralateral early visual cortex (Fig. 2C). The activation in the right occipital cortex was stronger than that in the left, which unlikely resulted from CGN’s eye movement during the scan because the accuracy in detecting illumination changes of the central ring was stable, regardless of whether the checkerboard sectors were presented in the left (84%) or right (85%) visual field. Instead, the weaker activation apparently reflected the lesion in the left occipitoparietal cortex extended to the upper portion of the occipital cortex. Consistent with this conjecture, the sector in the lower right visual field did not activate the upper portion of the occipital cortex in the left hemisphere. Importantly, the checkerboard sector in the upper right quadrant of the visual field activated the lower left occipital cortex properly. Taken together, the functionality of the left low-level visual cortex was at least partially restored after the lesion. That is, visual information may reach the high-
level visual cortex in the left hemisphere through the lower portion of the left occipital cortex. In line with this intuition, we observed that the left temporal cortex was properly activated by visual stimulation when comparing the neural activation for all visual stimuli (faces, words, objects and scrambled objects) versus the fixation baseline (Fig. 3B), although the magnitude of the activation was weaker than that in the right temporal cortex. The critical question, then, was whether the activation observed in the left temporal cortex was object-selective.

To examine the object selectivity in the left temporal cortex, we contrasted all objects (faces, words and objects) with scrambled objects (Fig. 3C) to identify regions that were sensitive to general object shapes. There was no significant selective response in the left temporal cortex, even at a liberal threshold (p < .05, uncorrected) (Fig. 3C, right). That is, although the left temporal cortex was properly activated by visual stimulation, the response was not object-selective. The fact that the left temporal cortex showed no selectivity for objects was unlikely accounted by insufficient power for two reasons. First, the right temporal cortex, which had received continuous visual inputs from the intact right early visual cortex since birth, showed selective responses for general object shapes (Fig. 3C, left). Further, with the contrast of faces versus objects, the face-selective FFA and fSTS were successfully localized in the right hemisphere (outlined in purple in Fig. 3B and C). The ROI-based analysis further revealed that the neural responses for faces in both the FFA and fSTS were higher than those for non-face objects (i.e., words and objects) (p < .002) (Fig. 3D). In addition, with the contrast of objects versus scrambled objects, the object-selective LO and pFs were localized in the inferior temporal cortex (outlined in green in Fig. 3B and C). Therefore, the temporal cortex in the right hemisphere showed proper selective responses for both faces and objects, similar to findings in normal individuals. Second, with the contrast of words versus objects, the VWFA, which is usually localized in the left hemisphere in normal individuals, was localized in CGN’s right hemisphere (outlined in blue in Fig. 3B and C). Because the VWFA is thought to be exclusively shaped by visual experiences (Baker et al., 2007), the fact that the VWFA was localized in the right hemisphere further suggested the critical role of visual inputs from the early visual cortex in forming the object selectivity of the high-level visual cortex. Interestingly, the presentation of words also activated the IFC, or Broca’s area in CGN’s left hemisphere, suggesting that language processing in CGN’s brain at a higher level was still left-hemisphere dominant, which is similar to normal individuals.

The difference in object selectivity between the left and right inferior temporal cortex suggests the important role of visual inputs from the early visual cortex at an early age in shaping the high-level visual cortex. To further validate this finding, three additional analyses were conducted. First, we asked whether the object selectivity observed in CGN’s intact right hemisphere was properly developed, unaffected by the impaired left hemisphere. To do this, we scanned six age- and sex-matched TDC, and identified their face- and object-selective regions in both hemispheres respectively (Fig. 4A). We found that CGN’s face-selective regions (FFA and fSTS) and object-selective regions (LO and pFs) were located within the anatomical distribution of the TDC’s (Fig. 4B). Table 1 shows the Montreal Neurological Institute (MNI) Talairach coordinates of the peak voxels in both TDC’s and CGN’s face- and object-selective regions. More importantly, the effect size of selectivity observed in CGN was not significantly different than that in the TDC for both objects (ps > .48) and faces (ps > .14) (Fig. 4C). Note that although the selectivity for faces in CGN’s FFA (.02) and fSTS (.10) was lower as compared with TDC’s, it was within 95% confidence interval of TDC’s in both FFA [−01, .31] and fSTS [.09, .25]. In addition, TDC’s left inferior temporal cortex also showed selective responses for faces and objects (Fig. 4A), in contrast to the absence of object selectivity in CGN’s left hemisphere. Taken together, it is CGN’s left temporal cortex that failed to develop normal object selectivity because of the disruption of visual inputs from early visual cortex at an early age.

Second, although the left early visual cortex was significantly activated by visual stimuli (vs fixation), the magnitude of the activation was lower than that in the right hemisphere. Therefore, it is possible that the absence of object selectivity in the inferior temporal cortex was accounted for by the low level of neural activation in the early visual cortex. To rule out this possibility, we performed an ANOVA analysis with factors being hemisphere (left vs right) and activation versus selectivity (Fig. 5). We found that although both the neural activation and object selectivity were higher in the right hemisphere (F(1,63) = 56.5, p < .001), there was a significant two-way interaction of hemisphere by activation versus selectivity (F(1,63) = 138.9, p < .001), suggesting that the object selectivity in the left inferior temporal cortex was disproportionally lower than the neural activation in the left early visual cortex. That is, the low level of neural activation in the early visual cortex cannot fully account for the absence of object selectivity in the inferior temporal cortex of the left hemisphere.

Finally, both the behavioral tests and self-reports suggested no visual deficits in the right visual field, whereas there was no selective response for objects in the left ventral visual pathway. One possible interpretation for the apparent inconsistency is that visual information from the right visual field may be transferred to the intact ipsilateral hemisphere possibly through thalamic commissural fibers or the callosum (e.g., Boire, Theoret, & Pito, 2001; Govindan et al., 2008; Nelles et al., 2002). Consistent with this intuition, the checkerboard sectors shown in the right visual field activated both contralateral and ipsilateral visual cortex, whereas the stimuli in the left visual field only activated the contralateral visual cortex (Fig. 6). This observation was further confirmed by a significant two-way interaction of stimuli (left vs right checkerboard sectors) by hemisphere (ipsilateral vs contralateral) (F(1,63) = 247.2, p < .001).

In sum, although the left temporal cortex was activated by visual stimulation, it showed no object-selective responses. In contrast, the right temporal cortex, which had received continuous visual inputs since birth, showed normal selectivity for objects.

4. Discussion

In this case study, we investigated the role of visual inputs at an early age in shaping the functional selectivity for objects in
the high-level visual cortex of a pediatric patient who suffered a subdural hematoma in the left occipitoparietal cortex at the age of one. Before surgery was conducted at the age of six, CGN’s visual perception in the right visual field was severely impaired by pressure from the hematoma on his left occipitoparietal cortex. However, six years after the surgery, behavioral tests suggested that the hemianopia was largely alleviated. Consistently, the meridian mapping showed that the lower portion of the left early visual cortex was activated by stimuli that were presented in the upper right quadrant of the visual field. Furthermore, the temporal cortex was able to respond to visual stimulation, suggesting that visual inputs

![Fig. 4](image)

**Fig. 4** — Comparison of the anatomical location and selectivity of face- and object-selective ROIs between CGN and six age- and sex-matched TDC. A) Face-selective regions (FFA and fSTS) and object-selective regions (LO and pFs) are outlined in purple and green (p < .05, uncorrected) for each control individual. The face-selective regions were defined by the contrast of faces versus objects, whereas the object-selective regions were localized by the contrast of objects versus scrambled objects. Capital letters are the initials of the participants. B) The location of the peak voxels in response to faces and objects in the ROIs of both TDC and CGN are marked on the surface of the fsaverage brain. Purple dots indicate TDC’s face-selective regions, whereas green dots indicate TDC’s object-selective regions. The location of the peak voxels from CGN is outlined in red. C) The effect size of the selectivity for faces in the FFA and fSTS and for objects in the LO and pFs are shown for both TDC and CGN. Note that the effect size of the selectivity in CGN was not significantly different from that in TDC.

**Table 1** — MNI Talairach coordinates of the peak voxels of the face-selective and object-selective regions.

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<th></th>
<th>TDC Left hemisphere</th>
<th>TDC Right hemisphere</th>
<th>CGN Right hemisphere</th>
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<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>FFA</td>
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<td>-56 ± 8</td>
<td>-20 ± 6</td>
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<tr>
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<tr>
<td>LO</td>
<td>-43 ± 10</td>
<td>-70 ± 9</td>
<td>5 ± 13</td>
</tr>
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Note that the posterior occipital cortex of CGN’s right hemisphere greatly expanded towards the left side, which may affect the accuracy of the coordinates of CGN’s face- and object-selective regions.

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from the early visual cortex to the high-level visual cortex were at least partially restored. However, the responses observed in the temporal cortex were not object selective, suggesting that the object selectivity of the high-level visual cortex was not properly developed, even after the visual inputs were restored. Together, the results of our study provided empirical evidence that visual inputs at an early age are critical for the development of object selectivity in the high-level visual cortex in the ventral pathway.

Our results are consistent with previous findings that high-level visual functions cannot develop properly without normal visual inputs (Maurer, Mondloch, & Lewis, 2007). One possible mechanism is that visual inputs from the early visual cortex are necessary to build the optimal neural infrastructure of the high-level visual cortex. More importantly, without visual inputs, the requisite neural connections may be lost through a competitive interaction between the hemispheres (Lewis & Maurer, 2009). Consistent with this intuition, we found that CGN’s right hemisphere was enlarged, encroaching on the space of the left hemisphere in the skull. Furthermore, contrary to previous studies where the VWFA is generally left lateralized (Cohen et al., 2000), we localized the VWFA in the right temporal cortex instead, suggesting that compensatory development of the word-selective responses occurred in the right homolog of the VWFA (Govindan et al., 2008; Nelles et al., 2002). In short, the basic neural architecture of the left temporal cortex might have been established at birth, but visual inputs at an early age are necessary to trigger the development of high-level visual functions (i.e., selective responses for a particular object category) in the temporal cortex.

Importantly, the lesion happened before CGN was six, suggesting that this period involved a critical period in the development of object selectivity in the visual cortex. That is, six years after surgery, the visual inputs from the early visual cortex to the high-level visual cortex were at least partially restored, but selective responses for objects were not yet observed in the high-level visual cortex. Therefore, it is likely that there might be a critical period for the development of

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high-level visual functions. The exact time frame of the critical period is unclear, but the results of a case study have suggested that the critical period might be as early as the age of two (Bova et al., 2008). In that study, the bilateral primary visual cortex was impaired by an acute attack of gliosis that occurred in a patient at the age of two years and six months. Although low-level vision, which includes motion perception and visual acuity, gradually recovered in the patient four years later, the recognition of objects in unusual perspectives or lighting was still impaired.

There are several limitations of this study. First, we observed that neural activation in the left early visual cortex was partially recovered, but object selectivity in the left inferior temporal cortex was still absent. This disproportional recovery from the lesion suggests the dissociation between the neural activation in the low-level visual cortex and the object selectivity in the high-level visual cortex. However, one may argue that the early and high-level visual cortex may interact in an additive or even multiplicative way; therefore, poor processing at an early level may be amplified at a later level, which affects the detection of object selectivity. Direct examination of the interaction between the early and later levels of visual processing during development may help resolving this alternative in future studies. Another limitation is that we did not test whether CGN’s behavioral performance in recognizing objects presented to the impaired hemisphere was fully restored at the time of the fMRI scan; further, it is unclear whether CGN’s high-level visual cortex in the impaired hemisphere will develop to the level of normal individuals in his adolescence or adulthood. On one hand, the human brain is highly malleable, even in adulthood (Levi, 2005; Ostrovsky, Andelman, & Sinha, 2006), and six years’ recovery after the surgery might not have been sufficient. In fact, recent studies have shown that the ability to recognize faces continues to develop late, reaching a peak after the age of thirty (Germaine, Duchaine, & Nakayama, 2011). Therefore, it is possible that the selectivity for objects might eventually develop in CGN’s adolescence or adulthood. On the other hand, the improvement of high-level visual functions may occur through cortical reorganization. Indeed, after unilateral lesion of the striate cortex, reorganization of networks is observed in the intact ipsilateral visual cortex possibly through the contralateral and ipsilateral visual cortex. Therefore, it is likely that visual information from the right visual field may reach the intact ipsilateral visual cortex possibly through the thalamic commissural fibers (Boire et al., 2001) or the callosum. Future diffusion tensor imaging studies may help elucidating the cortical reorganization.

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