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Activation of the Remaining Hemisphere Following Stimulation of the Blind Hemifield in Hemispherectomized Subjects

R. G. Bittar,*,† M. Ptito,*,‡ J. Faubert,‡ S. O. Dumoulin,* and A. Ptito*

**Montreal Neurological Institute and McGill University, Montreal, Canada; †Department of Anatomy and Histology, The University of Sydney, Sydney, Australia; and ‡Ecole d'Optométrie, Université de Montréal, Montreal, Canada*

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We used functional magnetic resonance imaging (fMRI) to investigate the neural substrates mediating residual vision in the "blind" hemifield of hemispherectomized patients. The visual stimuli were semicircular gratings moving in opposite directions on a dynamic random-dot background. They were specifically constructed to eliminate intra- and extraocular light scatter and optimize the activation of extrastriate cortical areas and their subcortical relays. Multislice T2*-weighted gradient echo (GE) echoplanar imaging (EPI) images (TR/TE = 4 s/45 ms, flip angle 90°) were acquired during activation and baseline visual stimulation. An activation minus baseline subtraction was performed, and the acquired *t* statistic map transformed into the stereotaxic coordinate space of Talairach and Tournoux. In seven normal control subjects, right hemifield stimulation produced significant activation foci in contralateral V1/V2, V3/V3A, VP, and V5 (MT). Significant activation was also produced in homologous regions of the right occipital lobe with left hemifield stimulation. Stimulation of the intact hemifield in hemispherectomized patients resulted in activation of similar areas exclusively within the contralateral hemisphere. Stimulation of the anopic hemifield produced statistically significant activation in the ipsilateral occipital lobe (putative area V5 or MT) and areas V3/V3A in the only subject with blindsight. We conclude that the remaining hemisphere may contribute to residual visual functions in the blind hemifield of hemispherectomized patients, possibly through the collicular–pulvinar route since the activated areas are known to receive their afferents from these subcortical nuclei.

INTRODUCTION

Contrary to traditional views (e.g., Holmes, 1918) destruction or deafferentation of the primary visual cortex does not always abolish all visual abilities in the corresponding visual field (see Stoerig and Cowey, 1997, for a review). When unconscious, the residual visual functions have been termed "blindsight" (Weiskrantz *et al.*, 1974). In a study where light scatter and eye movements were strictly controlled for, Tomaiuolo *et al.* (1997) demonstrated blindsight in two hemispherectomized patients by eliciting spatial summation across the vertical meridian. By measuring the reaction time to visual stimuli placed in the blind, intact, or both hemifields, these authors found a faster response following the simultaneous presentation of stimuli in the blind and intact fields than that elicited following presentation in the intact field only. No responses were elicited with sole presentations in the blind field or in the blind spot. These results were supported in a report on two hemispherectomized infants who were able to fixate targets presented in the visual hemifield contralateral to the surgical resection (Braddick *et al.*, 1992). Zones of residual vision, this time with awareness, were found in two adult subjects with functional hemispherectomy. Within these areas they could detect stimuli and perform simple shape discriminations (Wessinger *et al.*, 1996). Furthermore the capacity to discriminate between three-dimensional objects (Ptito *et al.*, 1987) and between simple patterns (Perenin, 1978) in the hemianopic field may also persist following hemispherectomy. Objective evidence that hemispherectomized humans are able to detect movement and discriminate velocity (Ptito *et al.*, 1991), but not direction (Perenin, 1991; Ptito *et al.*, 1991), has also been furnished.

Recently, however we have been unable to confirm the presence of blindsight and/or residual vision in hemispherectomized subjects (King *et al.*, 1996a, 1996b; Storig *et al.*, 1996; Faubert *et al.*, 1999). This apparent contradiction reinforces the common observation that individual differences among subjects exist. While some demonstrate total blindness, the phenomenological experience reported in the blind field by others appears context-dependent, i.e., under certain experimental conditions there could be a conscious experience qualified as "residual vision" (Ptito *et al.*, 1987, 1991; Wessinger *et al.*, 1996), while in others there is an uncon-

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scious visual sensitivity (Tomaiuolo *et al.*, 1997; Herter *et al.*, 1998).

Whereas ipsilesional extrastriate cortices have been proposed as responsible for blindsight in subjects with restricted posterior lesions, subcortical structures (such as the superior colliculi and/or the pulvinar thalami), possibly in conjunction with the remaining hemisphere, have been proposed as likely contenders in hemispherectomized subjects (Ptito *et al.*, 1991). The precise neural substrates and mechanisms for such residual visual abilities are, however, yet to be elucidated since reports have so far provided only indirect evidence regarding the anatomical structures mediating residual vision in the blind hemifield.

To investigate these neural pathways more directly, fMRI was used in three hemispherectomized subjects who participated in a blindsight study (Tomaiuolo *et al.*, 1997). To the best of our knowledge, this is the first functional neuroimaging study with hemispherectomized subjects aiming to visualize the cerebral regions involved in blindsight. A conference abstract of part of this study has been published (Bittar *et al.*, 1998).

MATERIALS AND METHODS

Subjects

Three subjects who had previously undergone partial or complete hemispherectomy (1 left, 2 right) for the relief of intractable epileptic seizures participated in the studies (Table 1). All subjects had a complete hemianopia with no macular sparing in the visual field contralateral to the side of resection as evaluated with standard perimetry techniques (see Ptito *et al.*, 1991). For comparison purposes, seven normal volunteers also participated (4 females, 3 males; age 18–44 years). All studies were performed with the informed consent of the subjects and were approved by the Montreal Neurological Institute Research Ethics Committee.

TABLE 1

Clinical Details of Three Hemispherectomized Subjects

Subject	I.G.	J.B.	D.R.
Clinical details	Female 45 years	Male 32 years	Female 25 years
	Right anatomical hemispherectomy	Left functional hemispherectomy	Right modified functional hemispherectomy
	Porencephaly	Porencephaly	Rasmussen's encephalitis
	Seizure onset at 7 years	Seizure onset at 5 years	Seizure onset at 5 years
	Surgery at 13 years	Surgery at 20 years	Surgery at 17 years
	Full-scale IQ 79	Full-scale IQ 88	Full-scale IQ 83
	No blindsight	No blindsight	Blindsight

Visual Stimulus

The visual stimuli were generated on a MacIntosh Powerbook 160 using a modified program from the Vision Shell (Ptito *et al.*, 1999). The baseline condition comprised viewing randomly moving dots (1 Hz; 128 luminance grey levels). The activation condition consisted of a black and white semicircular ring (inner radius 11.4°, outer radius 18.6°) with two embedded gratings (1.5°) moving vertically in opposite directions (6.5 Hz), presented unilaterally on the background of randomly moving dots. The purpose of the background of random dots was to prevent extraocular light scatter into the surrounding visual field (Faubert *et al.*, 1999). During the activation and baseline conditions, the subject fixated on a small black circle in the center of the screen. The visual stimulus was projected onto a rear-projection viewing screen placed at the end of the bore of the magnet, and the projection screen was viewed by means of a mirror mounted above the eyes at an angle of approximately 45°. A black sheet was used to cover the inside of the scanner in order to minimize light reflection and scatter.

Functional Scanning

Blood oxygen level-dependent (BOLD) fMRI was used to examine the pattern of activation in each occipital lobe upon stimulation of the contralateral visual hemifield. Multislice T2*-weighted gradient echo (GE) echoplanar imaging (EPI) images (TR/TE = 4 s/45 ms, flip angle 90°) were acquired with a Siemens Magnetom Vision 1.5T MRI scanner in planes through the occipital cortex, parallel to the calcarine sulcus (10–12 contiguous 6 mm slices). These studies were conducted with the subjects lying on their back with a circularly polarized receive-only surface-coil centered over the occipital poles. Head position was fixed by a foam headrest and a combination of immobilizing hearing protectors and a bar pressing on the bridge of the nose. Prior to the fMRI studies, T1-weighted anatomical MRI images were acquired with the surface-coil in place, before the commencement of the functional scans. This utilized a three-dimensional GRE sequence (TR = 18 ms; TE = 10 ms; flip angle 30°) and yielded approximately 80 256 × 256 sagittal images.

Anatomical MRI and Coregistration

In all subjects a T1-weighted anatomical MRI scan (TR = 18 ms; TE = 10 ms; flip angle 30°) was acquired yielding approximately 160 256 × 256 sagittal images comprising 1-mm^3 voxels. The images were mapped into a common standard (stereotaxic) space, using an automated algorithm that maximized the cross-correlation between the images and the average of 305 normal MRI scans manually registered into the coordinate space of Talairach and Tournoux (Woods *et al.*, 1992).

Image Analysis

All fMRI time series data were subtracted from the first baseline image and examined for motion-induced misregistration. Locally developed automated registration software, based on a cross-correlation measure, was used to correct for any in-plane movement. The anatomical MRI scans were corrected for intensity nonuniformity and mapped into the common standard (stereotaxic) space of Talairach and Tournoux (1988). The surface-coil anatomical scans were aligned with the head-coil anatomical scans using an automated script combining correction for the intensity gradient and intrasubject registration. The functional data were blurred with a 6-mm full-width-at-half-maximum Gaussian filter and analyzed using a Spearman rank order statistical test. An activation minus baseline subtraction was performed, and the acquired t statistic map was transformed into the stereotaxic coordinate space of Talairach and Tournoux (1988) by combining the transformation files from the previous two image registration steps. t Values corresponding to P values smaller than 0.05 were considered significant. For the controls, individual activation patterns were examined, and the results for all subjects were averaged for group analysis.

RESULTS

Normal Subjects (Controls)

As expected, activation patterns were symmetrical and consistent across subjects, with statistically significant ($P < 0.05$) activation in the contralateral areas V1/V2, V3/V3A, VP, and V5. After the results of right hemifield activation were averaged, significant activation foci ($P < 0.01$) were observed in V1/V2 (calcarine sulcus; Talairach coordinates −10, −86, 4.6), V3/V3A (occipital pole; −17, −93, 22), VP (lingual gyrus; −15, −77, −2.9), and V5 (parieto–temporo–occipital junction; −50, −72, 7.5). Statistically significant activation was produced in homologous regions of the right occipital lobe with left hemifield stimulation (Fig. 1). In all studies, activation was confined to the cerebral hemisphere contralateral to the stimulated visual field. A directed search did not reveal significant activation within the superior colliculi or pulvinar.

Hemispherectomized Subjects

Stimulation of the intact hemifield resulted in several areas of statistically significant activation ($P < 0.01$) exclusively within the contralateral occipital lobe (Table 2; Fig. 2) in all experimental subjects. Stimulation of the anopic hemifield in the two subjects who did not exhibit blindsight in the Tomaiuolo *et al.* study (1997) failed to yield statistically significant activation.

Stimulation of the hemifield contralateral to the hemispherectomy resulted in statistically significant activation in the ipsilateral occipital lobe in one subject with blindsight (Fig. 3). Four activation foci were obtained in this subject with right hemispherectomy (DR): (i) left temporo-occipital junction: putative V5; t = 10.7; −48, −75, −2; (ii) left occipital pole: V3/V3A; t = 7.9; −24, −93, −2; (iii) left cuneus: V3/V3A; t = 7.7; −12, −87, 16; and (iv) left occipital pole: V3/V3A; t = 6.4; −24, −86, 24. No activation of the primary visual cortex was observed. The subject reported awareness of something moving on her left, but could not describe it.

DISCUSSION

Before we enter the discussion and interpretation of the results obtained here, several methodological considerations are necessary: (1) due to magnetic field considerations, eye movements could not be monitored continuously. While we cannot be certain that lateral eye movements did not take place, the failure to activate ipsilateral cortex in normal control subjects suggests that possible inadvertent eye movements did not produce significant activation. In addition to being well-trained to fixate centrally, the hemispherectomized subjects were constantly reminded to maintain fixation and they showed similar areas of activation as the control subjects when their intact field was stimulated indicating that the stimuli were well lateralized; (2) light scatter was minimized by a carefully designed stimulus (Ptito *et al.*, 1999) and by lining the bore of the scanner with a black sheet to eliminate reflection. The failure to activate ipsilateral occipital cortex in the control group is in keeping with adequate control of light scatter from the stimuli and potential reflections off the scanner.

With these methodological considerations, we used fMRI to study the pattern of activation obtained with stimulation of the blind and intact visual hemifields in three subjects with hemispherectomy who participated in a blindsight study (Tomaiuolo *et al.*, 1997). A control group of normal volunteers was used for the purpose of comparison. In the latter group, all showed statistically significant activation exclusively within the contralateral hemisphere. In almost all of these normal subjects we obtained statistically significant activation in four visuotopically organized cortical regions (V1/V2, V3/V3A, VP, and V5). These same areas were activated in the remaining hemisphere of the three hemispherectomized subjects upon stimulation of their intact field.

As is commonly reported, individual differences appeared with blind field stimulation. In the two subjects who did not show blindsight in the strictly controlled Tomaiuolo *et al.* study (1997; IG and JB), no statistically significant activation was produced. In the one subject with blindsight we tested (DR), blind field

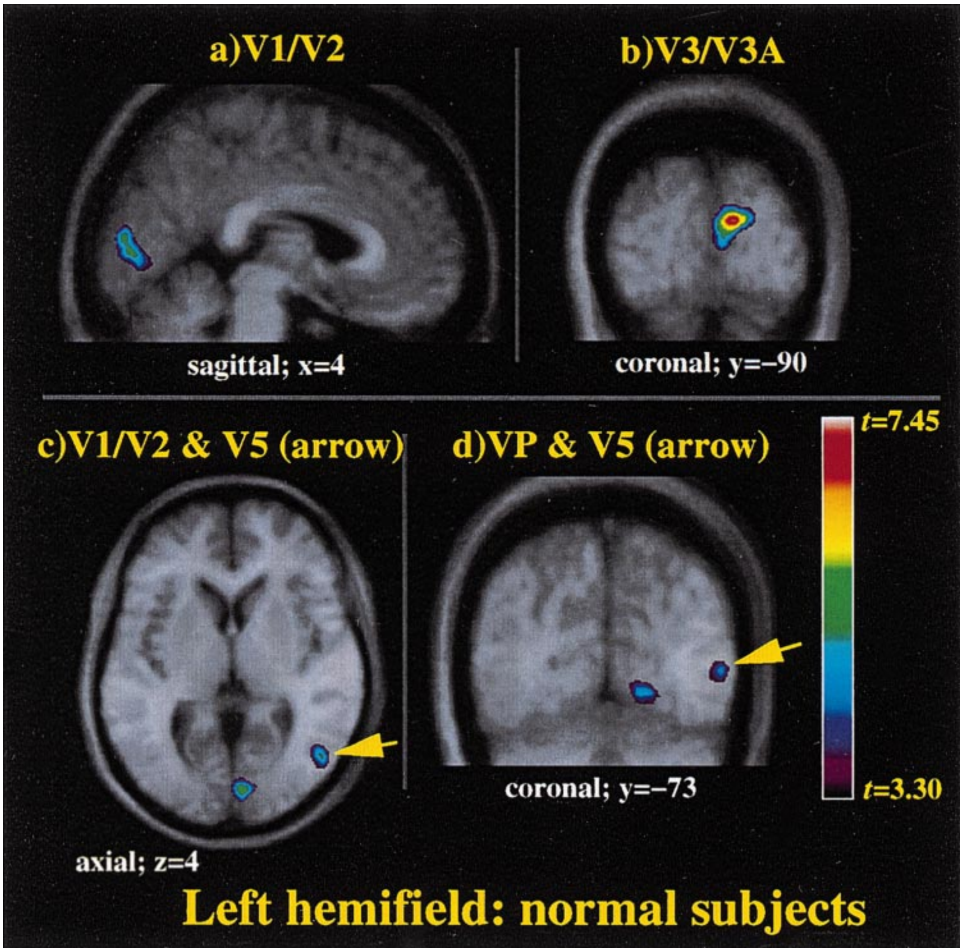


FIG. 1. Averaged activation following stimulation of the left hemifield in seven normal subjects. Statistically significant ($P < 0.01$) activation foci were observed in the right V1/V2, V3/V3A, V5, and VP. No significant activation foci were present in the ipsilateral hemisphere (either in individual analyses or group average).

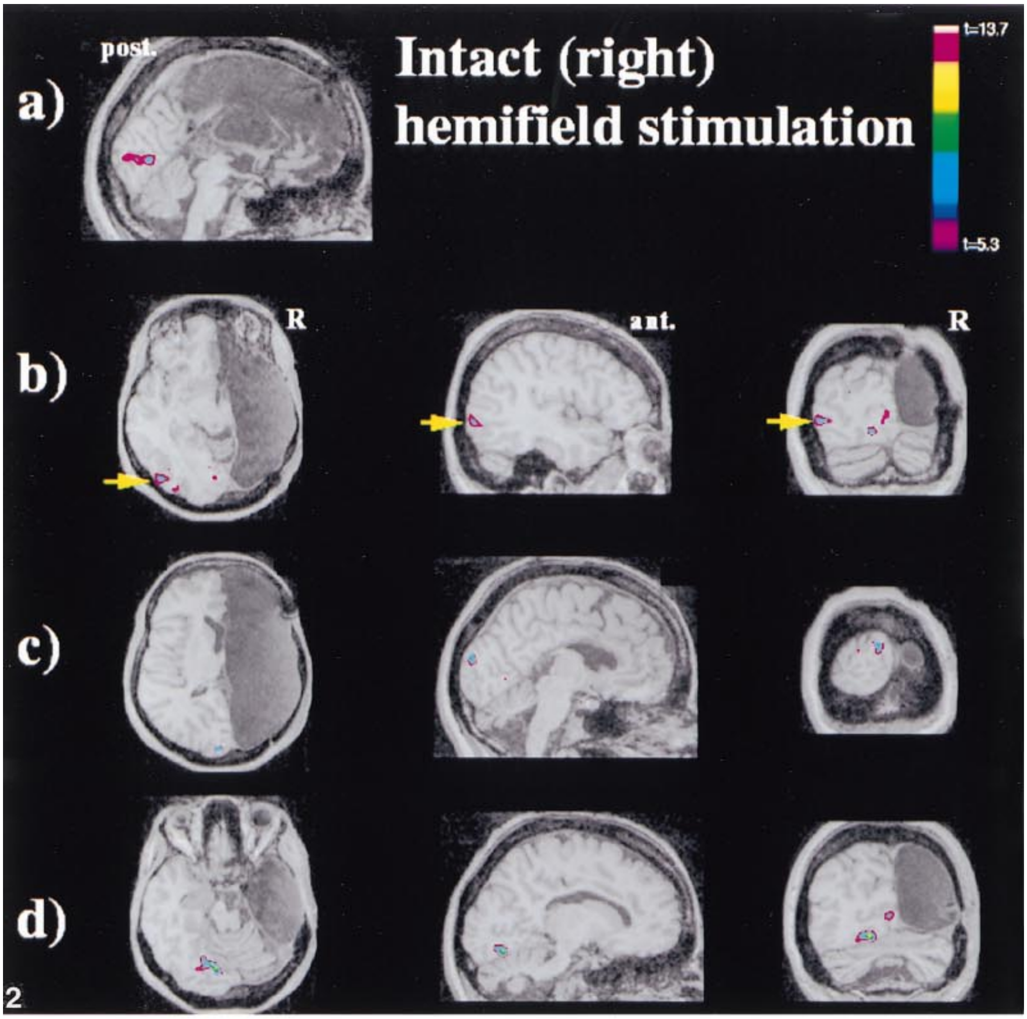
stimulation produced activation of the ipsilateral extrastriate visual cortices (V3/V3A and V5), but no activation of the primary visual cortex or VP (which were activated strongly on intact hemifield stimulation). In no case was activation observed in the superior colliculi or pulvinar, although it is possible that the resolution and sensitivity of the fMRI does not allow visualization of activation in such small structures.

Potential Anatomical Substrates of Blindsight

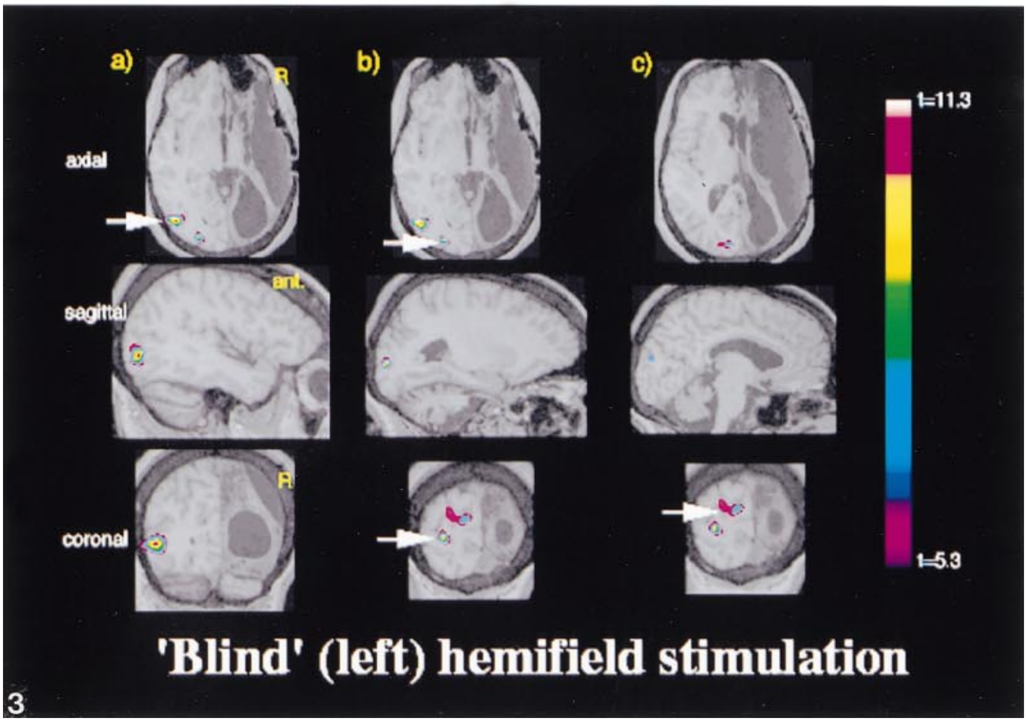
The results of the present study are consistent with the possibility that the remaining hemisphere plays a role in the mediation of blindsight and/or residual visual abilities in the blind field. This would be achieved either by a process of cortical plasticity and/or by utilization of existing neural pathways such as subcortical nuclei. Several observations have provided support for the superior colliculi as a likely mediator of residual visual function following removal or destruction of the striate and extrastriate cortices. Monkeys who have had their striate cortex removed are able to localize visual stimuli in their blind hemifield (Keating, 1975), discriminate wavelength (Pasik and Pasik, 1980; Keating, 1979), simple shapes and patterns (Kluver, 1941; Pasik *et al.*, 1969, 1976; Schilder *et al.*, 1972), as well as velocity (Keating, 1980). These abilities are abolished following additional destruction of the ipsilateral superior colliculus (Mohler and Wurtz, 1977; Rodman *et al.*, 1990). In hemispherectomized infant monkeys that detect stimuli in their blind hemifield,

FIG. 2. Stimulation of the intact (right) hemifield in I.G. resulted in statistically significant ($P < 0.01$) activation in the contralateral occipital lobe. Activation foci were observed in (a) V1/V2, (b) V5, (c) V3/V3A, and (d) VP.

FIG. 3. "Blind" (left) hemifield stimulation, in a subject (D.R.) who was previously shown to possess blindsight, resulted in ipsilateral extrastriate activation foci: V5 (a) and V3/V3A (b and c).


a)
post.
Intact (right)
hemifield stimulation
t=13.7
t=5.3
b)
R
ant.
R
c)
d)

2


a)
b)
c)
R
axial
ant.
sagittal
R
coronal
t=11.3
t=5.3
'Blind' (left) hemifield stimulation

3

TABLE 2

Statistically Significant ($P < 0.01$) Activation Foci Following Intact Hemifield Stimulation in Three Hemispherectomized Subjects

Subject	I.G.	J.B.	D.R.
Intact hemifield stimulation	1. $t = 12.7$ Talairach coordinates (−11.8, −80.5, −18.4) Left lingual gyrus VP	1. $t = 22.8$ (4.1, −78.9, −8.7) Right calcarine sulcus/lingual gyrus V1/V2	1. $t = 10.9$ (−11.9, −86.6, 25.8) Left cuneus V3/V3A
	2. $t = 10.0$ (−6.2, −96.7, 11.6) Left occipital pole V3/V3A	2. $t = 15.1$ (6.2, −92.6, 29.8) Right cuneus V3/V3A	2. $t = 10.6$ (−20.3, −66.5, −16.4) Left lingual gyrus VP
	3. $t = 8.2$ (−2.3, −74.5, −4.5) Left calcarine sulcus V1/V2	3. $t = 12.8$ (11.9, −88.5, 13.6) Right occipital pole V3/V3A	3. $t = 7.6$ (−42.6, −80.7, 9.3) Left temporo-occipital junction V5
	4. $t = 7.6$ (−20.7, −92.5, 7.6) Left occipital pole V3/V3A	4. $t = 10.3$ (23.8, −58.1, −8.4) Right fusiform gyrus VP	4. $t = 6.5$ (−25.6, −88.6, 1.4) Left occipital pole V3/V3A
	5. $t = 8.0$ (−44.1, −82.6, −6.1) Left temporo-occipital junction V5	5. $t = 8.8$ (45.8, −80.5, 9.6) Right temporo-occipital junction V5	5. $t = 5.7$ (−12.1, −80.7, 1.3) Left calcarine sulcus V1/V2

anatomical and histochemical studies revealed transneural retrograde degeneration of many retinal ganglion cells, a large reduction in volume of the ipsilateral dLGN, but only a very slight reduction in volume of the ipsilateral superior colliculus (Ptito *et al.*, 1996). In monkeys, the superior colliculi receive direct input from both the retina and the striate cortex and contain a complete representation of the visual field (Schiller, 1972). In addition, cells in the superior colliculi respond most vigorously to moving objects (Humphrey, 1968; Moors and Vendrik, 1979). The two superior colliculi communicate with each other via tecto-tectal projections (Edwards, 1977; Wallace *et al.*, 1990; Beehan *et al.*, 1996), and provide a potential channel to extrastriate visual cortices, most notably V5 (MT), via the pulvinar (Cowey *et al.*, 1994). This middle temporal cortex contains a large contingency of direction-selective neurons, and these neurons remain direction-selective following ablation of the striate cortex (Rodman *et al.*, 1989). Subsequent collicular ablation extinguishes this direction selectivity (Rodman *et al.*, 1990). Thus the ability to discriminate the direction of motion relies upon the integrity of not only the superior colliculus, but also the extrastriate cortex. This is supported by human studies (Perenin, 1991; Ptito *et al.*, 1991; King *et al.*, 1996) in which hemispherectomized patients (with an absence of striate and extrastriate cortex, but a presumably intact superior colliculus) demonstrate an inability to discriminate the direction of motion in their blind field (horizontal motion or motion-in-depth).

Evidence for intercollicular interaction was also provided in studies showing the presence of a spatial summation effect across the vertical meridian (Zihl and von Cramon, 1979; Tomaiuolo *et al.*, 1997). Further evidence of the role of subcortical mediation of the summation effect has been produced by Reuter-Lorenz *et al.* (1995), who showed the existence of an interfield summation effect in the absence of the corpus callosum and other cortical commissures.

Preservation of the superior colliculi following hemispherectomy, in the presence of a degenerated geniculocalcarine pathway, adds weight to their putative role in the mediation of residual visual functions in the monkey (Ptito *et al.*, 1996) and in humans (Ueki, 1966).

Another possible explanation of residual visual abilities in hemispherectomized subjects is cortical plasticity. The existence of cortical plasticity is supported by findings in humans that visual function may improve substantially with time following striate cortex destruction (Weiskrantz, 1974, 1980; Zihl, 1981; Ptito *et al.*, in press). Damasio *et al.* (1975) reported a case of hemispherectomy in a 20-year-old woman without hemianopia. This patient had sustained a severe closed head injury at age 5 and had bilateral optic nerve atrophy and concentric retraction of both visual fields prior to surgery. Following the resection, the patient actually demonstrated an increase in the visual field of one eye. More recently, Ptito *et al.* (1999) reported a similar visual field recovery in a patient with early occipital lobe damage. Taken together these results furnish some evidence that the human visual system is capable of adaptation or reorganization following major structural misadventure.

While the anatomical and physiological basis of blindsight in hemidecorticated subjects may be a combination of both the retinotectal system as well as plasticity of the unaffected cerebral cortex, the potential role of the intact occipital cortex should be considered. A vital issue is the route by which information from one visual hemifield reaches the ipsilateral cortex. Aside from transcallosal pathways, there are no known direct pathways for the transmission of visual information to the ipsilateral occipital lobe. It is conceptually possible for such information to occur via tecto-tectal pathways through the pulvinar or via direct controlateral retino-pulvinar projections, with eventual arrival at the ipsilateral extrastriate cortices (see Ptito *et al.*, 1999). The activation of V5 and V3/V3A in the remaining hemisphere of our hemispherectomized subject with blindsight supports a role of the remaining extrastriate cortices in the mediation of residual vision.

CONCLUSION

Using fMRI, we demonstrated activation of the ipsilateral extrastriate cortices in a patient with blindsight following hemispherectomy. We conclude that the contralesional occipital cortex, possibly in conjunction with its subcortical afferents, may be an important anatomical substrate in the mediation of residual visual abilities following the unilateral destruction or removal of striate and extrastriate cortex.

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