

Alterations of the visual pathways in congenital blindness

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Received: 16 July 2007 / Accepted: 8 January 2008 / Published online: 26 January 2008
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Abstract We used whole brain MRI voxel-based morphometry (VBM) to study the anatomical organization of the visual system in congenitally blind (CB) adults. Eleven CB without a history of visual perception were compared with 21 age- and sex-matched normal-sighted controls (NS). CB showed significant atrophy of the geniculostriate system, encompassing the optic nerves, the optic chiasm, the optic radiations and the primary visual cortex (BA17). The volume decrease in BA17 reached 25% in both hemispheres. The pulvinar and its projections to the associative visual areas were also dramatically altered, BA18/19 and the middle temporal cortex (MT) showing volume reductions of up to 20%. Additional significant white matter alterations were observed in the inferior longitudinal tract and in the posterior part of the corpus callosum, which links the visual areas of both hemispheres. Our data indicate that the afferent projections to the visual cortex in CB are

largely atrophied. Despite the massive volume reductions in the occipital lobes, there is compelling evidence from the literature (reviewed in Noppeney 2007; Ptito and Kupers 2005) that blind subjects activate their visual cortex when performing tasks that involve somatosensory or auditory inputs, suggesting a reorganization of the neural pathways that transmit sensory information to the visual cortex.

Keywords Voxel-based morphometry · Grey matter · White matter · Geniculostriate system · Extrastriate cortex · Blindness

Introduction

Blind people have to rely on other sensory modalities, such as audition and touch, to be able to function and interact with the visual world. Although the visual cortex of CB is completely deprived of visual input since birth, it shows a supra-normal resting metabolism as measured by PET (De Volder et al. 1997). In addition, several studies using a variety of brain investigation tools conducted in proficient Braille readers have shown task-induced activation of the visual cortex by non-visual input (reviewed in Sadato 2005; Sathian 2005; Ptito and Kupers 2005).

Animal studies have shown that early brain lesions can lead to altered-connectivity patterns in the adult brain (for recent reviews see Ptito and Desgent 2006; Ptito and Kupers 2005). For example, the destruction of the superior colliculus and ascending auditory pathways leads to the formation of permanent and novel retinal projections to non-visual thalamic nuclei, such as the medial geniculate nucleus, that normally mediates audition (Sur et al. 1988; Frost et al. 2000). These abnormal retinal projections are retinotopically organized and form functional synapses

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(Frost and Métin 1985; Campbell and Frost 1988). Neurons in the auditory cortex of these rewired animals possess visual receptive field properties similar to those of neurons in primary visual cortex (Ptito et al. 2001). In addition, the newly formed pathway from the retina to the auditory cortex can mediate visually guided behaviors in the absence of the normal retino-geniculate pathway (Frost et al. 2000; Von Melchner et al. 2000) suggesting the presence of a cross-modal plastic process.

The anatomical correlates of cross-modal plasticity in humans remain largely unexplored. Breitenseher et al. (1998), using subjective analysis of MRI's, found atrophy of the optical pathways, but not of the occipital cortex, in a group of 12 congenitally blind patients. Using VBM, Noppeney et al. (2005) showed reductions of the optic chiasm, the optic radiations and the extrastriate cortex (BA18) in a mixed group of early and late blind subjects. The authors also reported increased grey matter and white matter tracts in primary sensory and motor cortices. A diffusion tensor imaging (DTI) and tractography (DTT) study in a small group of five congenitally blind subjects, of whom, two had light sensitivity, reported atrophy of the optic nerve, the optic chiasm and the optic tracts (Shimony et al. 2005). However, no grey matter decreases were found in the striate cortex; neither did the authors mention grey or white matter increases in the primary somatosensory or motor cortex. In a more recent DTI investigation, an increase in cortico-spinal tracts in early blind men, but not in early blind women has been found (Yu et al. 2007). A VBM study in a group of 14, mostly late-blind subjects, of whom, only two were born blind, reported reduced volumes of the optic tract and the optic radiations, and grey matter losses in BA17/18 but not in higher extrastriate areas (Pan et al. 2007). Finally, Liu et al. (2007) used resting state fMRI and described altered functional connectivities within the visual cortices and between the visual cortex and other cortical structures, such as the parietal, frontal and temporal lobes, in the blind.

It is clear from the above that there is a large variability in reported results. This may result from the fact that the studies used different methodologies (VBM, DTI, DTT, resting state fMRI), small study samples and different study populations (congenital vs late blind). Many uncertainties remain, especially, concerning the extent of the atrophy in the various occipital cortical areas and the integrity of their afferent and efferent projections. The aim of this study was therefore to use VBM to further investigate the organization of the white and grey matter in a large sample of congenitally blind subjects, who never had any visual experiences. We hypothesized that all components of the two visual systems would be altered, in particular the retino-geniculo-calcarine and the retino-colliculo-pulvinar pathways.

Materials and methods

Subjects

We studied 11 CB (6M, 5F) and 21 NS (11M, 10F). All blind subjects were born blind and had no history of light perception. Average ages of CB and NS were 35.6 (range 20–54) and 33.0 (range 22–68) years, respectively ($P > 0.05$). Demographic data and the causes of blindness are summarized in Table 1. All subjects gave informed consent and the study protocol was approved by the local research ethics committee.

MRI acquisition

Subjects were recruited from the “Institut Nazareth et Louis Braille” in Montreal (Canada). Fast spoiled gradient echo 3D T1 images were acquired on a 1.5T Siemens Vision scanner using a standard head coil. Sequence parameters (TI/TR/TE) were 450/106/42 ms, single acquisition, a flip angle of 20° and a spatial resolution of $0.94 \times 0.94 \times 1 \text{ mm}^3$. Images were acquired in the axial plane.

VBM

Spatial pre-processing of the brain volumes was performed according to the optimized VBM protocol (Good et al. 2001) using SPM2 (Wellcome Department of Imaging Neuroscience, London, UK) and in-house software written in Matlab (MathWorks, Natick, MA, USA). First, a customized anatomical template was created based on the brain of all 32 participants. This involved spatially normalizing each of the anatomical images to the MNI/ICBM-152 standard template (Montreal Neurological Institute/International Consortium for Brain Mapping Template), which approximates Talairach space (Talairach and Tournoux 1988). This first normalization step was achieved using a

Table 1 Blind subjects characteristics

	Sex	Age	Cause of blindness
EB1	M	36	Retinopathy of prematurity
EB2	F	49	Retinopathy of prematurity
EB3	M	41	Retinitis pigmentosa
EB4	F	24	Detached retina
EB5	M	38	Retinopathy of prematurity
EB6	F	31	Glaucoma, aniridia
EB7	M	20	Leber's congenital amaurosis
EB8	M	34	Glaucoma
EB9	M	23	Congenital cataract
EB10	F	29	Retinoblastoma
EB11	F	54	Retinopathy of prematurity

12-parameter affine transformation. The normalized images were segmented into grey matter (GM), white matter (WM) and CSF using a mixture of Gaussian models (Ashburner and Friston 1997). An average image of all normalized T1-weighted anatomical and tissue volumes was then created and smoothed with a Gaussian kernel of 8 mm full-width half maximum. In the second normalization step, a 12-parameter affine transformation was used to match the grey (or white) matter images of each individual to the grey (or white) matter template and refined by using 16 non-linear iterations, medium regularization, and a 25-mm cut-off. A Jacobian modulation was applied to the data to preserve the absolute regional amount of grey (or white) matter from distortions introduced in the normalisation (Ashburner and Friston 2000). Each normalised, segmented and modulated, image was finally smoothed with an 8-mm FWHM kernel. The number of voxels in each tissue image (GM and WM) provided the total volume of the tissue. Moreover, the averaged value of GM volumes was extracted using pre-defined probabilistic regions of interest: BA 17 and 18 (Amunts et al. 2000) and V5/MT+ (Malikovic et al. 2007) using the Anatomy Toolbox (v 1.5; Eickhoff et al. 2007). Voxels with a probability of <10%, belong to each specific ROI, were excluded from the calculations.

Statistics

Statistical analyses were performed using the general linear formulation of SPM2. Global grey (or white) matter was included in the model as an extra regressor. Two types of models were constructed. The first one includes age as a confounding variable and the second one includes age and sex as confounds. We investigated differences in grey matter and white matter volumes between CB and NS using analysis of covariance (ANCOVA). The tissue images of CB and NS subjects were proportionally scaled to total grey (or white) matter volume with the global mean of 100, adjusting for either age or age and sex. Therefore, each region of group difference represented the difference in the percentage of total grey/white matter volume between the groups. A proportional scaling masking procedure was applied with a threshold of 0.2 such that the voxels with a probability of <20% belonging to a tissue type were excluded from the analysis. Statistical parametric maps (SPMs) were thresholded at $P < 0.05$ corrected for multiple comparisons with the false discovery rate (FDR) algorithm implemented in SPM2 (Genovese et al. 2002).

Image display and figure captions of the final results were achieved using MRIcro software (Rorden and Brett 2000). The anatomy toolbox was used for localization of cortical areas and fiber tracts (Burgel et al. 2006). The resulting structure identification was checked using the Talairach atlas (Talairach and Tournoux 1988), especially

when the cluster of differences was not identified by the anatomy toolbox.

Results

Compared to normal-sighted subjects, congenitally blind subjects showed a significant reduction of total brain volume, and grey and white matter volumes ($P < 0.05$) (Fig. 1).

Grey matter

A voxel-by-voxel group comparison with age as confound of no interest revealed significant bilateral decreases in grey matter volume of all structures belonging to the visual pathways in CB (Fig. 2a, red). At the thalamic level, significant reductions were found in the dLGN bilaterally and in the right posterior pulvinar nucleus. At the cortical level, significant volume decreases were observed in both occipital lobes, particularly in the region of the striate (BA17) and extrastriate cortex (BA18 and 19). The middle temporal gyrus (area MT?) also showed reduced GM volume bilaterally. MNI coordinates, cluster volumes and z -scores are presented in Table 2. The results of the VBM analysis including both age and sex as confounds of no interest gave the same results with this difference that the GM reduction in the pulvinar became sub-significant.

Using the anatomy toolbox, we compared the volume reductions in visual cortical regions between CB and NS. CB subjects showed on the average a 25% decrease in volume in area 17 (left 26%, right 25%), a 20% decrease in area 18 (left 20%, right 19%) and a 20% reduction in puta-

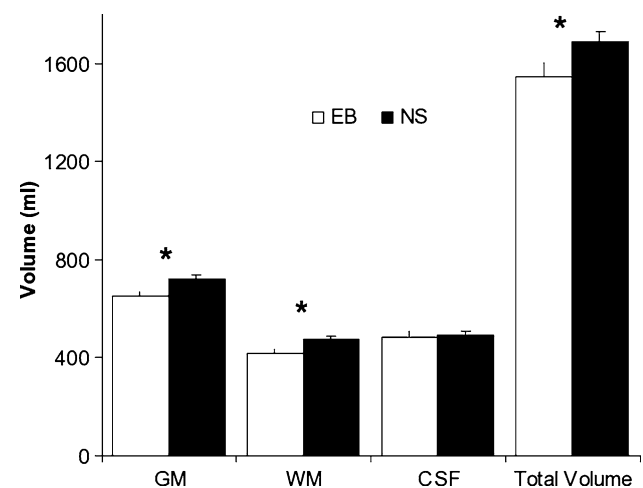


Fig. 1 Total brain grey and white matter volume reductions in the congenitally blind (CB) compared to normal seeing controls (NS). Values are expressed in mm³ and differences between groups were significant at $P < 0.05$ (two-tailed unpaired Student's t -test)

Fig. 2 a Regional grey and white matter differences between CB and NS. The volume differences are presented on horizontal sections for grey (*red*) and white (*blue*) matter. *Left side* of the figure refers to the left side of the brain. CB < NS: volume decreases for blind relative to sighted subjects. Note that all components of the visual system are reduced in volume. **b** Histograms illustrating volume reductions in the visual cortical areas in the cuneus (BA 17), extrastriate (BA18) and middle temporal lobe (putative MT). ****P* < 0.005

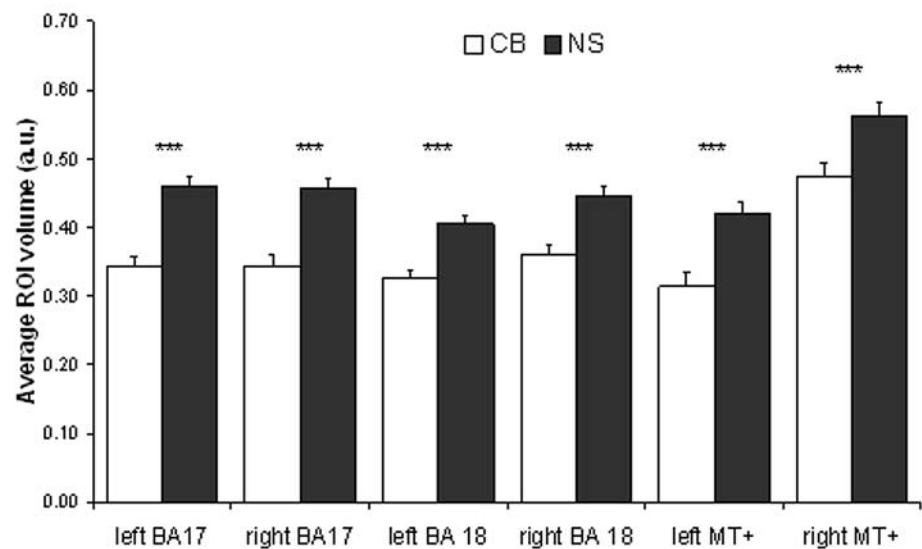
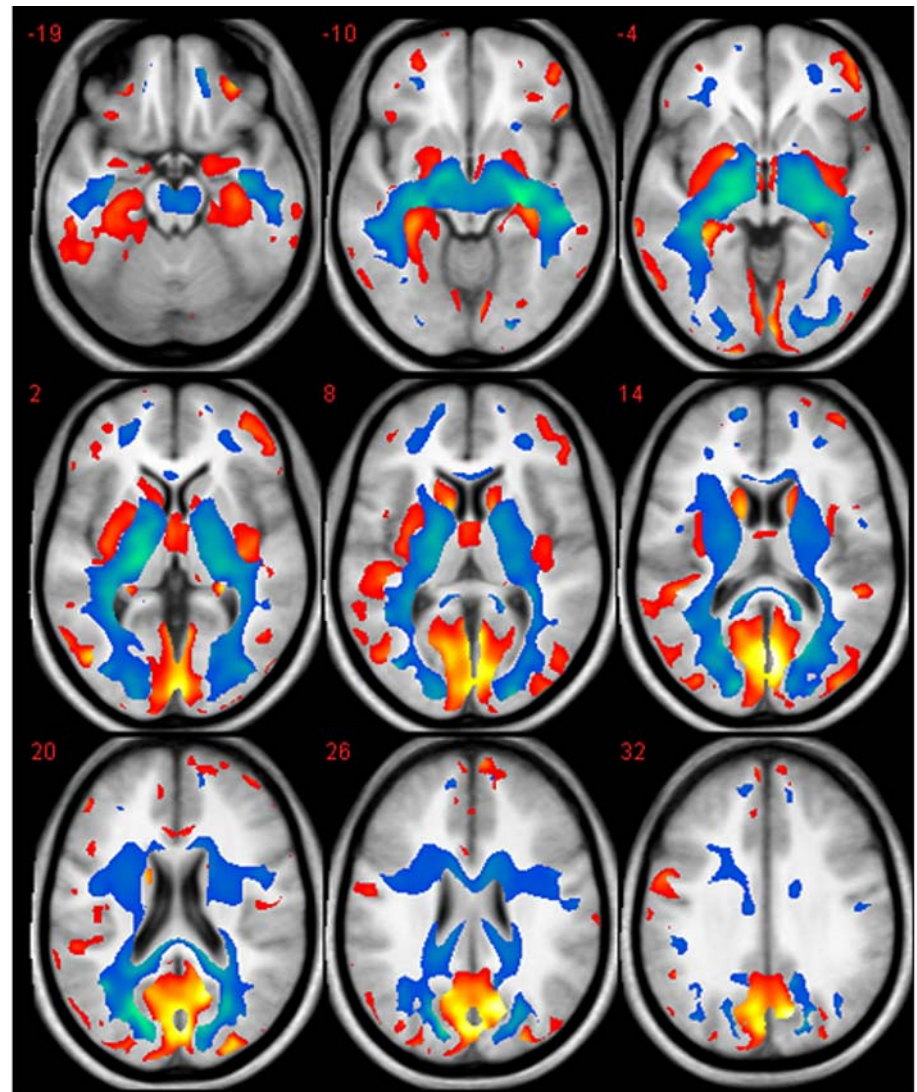


Table 2 Volume reductions in visual structures in congenitally blind subjects (including age as confound of no interest)

	BA	Side	MNI coordinates (mm)			Cluster extent (voxels/mm ³)	Corrected <i>P</i> (cluster)	<i>P</i> (fdr)	<i>Z</i> -score
			<i>x</i>	<i>y</i>	<i>z</i>				
Grey matter									
Cuneus	17	Bilat.	0	−88	4	40647	<0.001	<0.001	5.24
Cuneus	18	Bilat.	5	−75	14		<0.001	<0.001	5.82
Cuneus	19	Bilat.	4	−79	24		<0.001	<0.001	5.79
Precuneus	7, 18–19	Left	−12	−61	27		<0.001	<0.001	4.93
	7, 18–20	Right	12	−70	29		<0.001	<0.001	5.78
Middle temporal	37	Left	−45	−72	4	30187	<0.001	<0.001	5.89
	37	Right	46	−59	3	3897	0.19	0.01	3.34
LGN	–	Left	−28	−14	−6	30187	<0.001	0.04	2.69
	–	Right	24	−19	−9	7023	0.02	0.03	3.07
Pulvinar	–	Right	12	−31	1	27	1.00	0.04	2.59
White matter									
Optic tract	–	Bilat.	−16	−11	−5	157645	<0.001	<0.001	5.30
Optic radiations	–	Left	−22	−71	19		<0.001	<0.001	5.59
	–	Right	25	−65	16		<0.001	<0.001	5.00
Inferior longitudinal fasciculus	–	Left	−27	−24	−6		<0.001	<0.001	5.23
	–	Right	27	−19	−9		<0.001	<0.001	5.81
Splenium of the corpus callosum	–	Bilat.	18	−45	18		<0.001	<0.001	4.55

P (fdr) is the probability of differences of the peak voxel between EB and controls corrected for false discovery rate

P (cluster) is the corrected probability of differences at the cluster-level

tive area MT (left 25%, right 16%). These results are illustrated in Fig. 2b.

White matter

Blind subjects showed significant volume reductions of the optic nerves, the optic radiations and the optic tracts (Fig. 2a, blue). Visual inspection of the MRIs revealed that the optic chiasm was atrophied in five CB and reduced in volume in five others (Fig. 3). Additional white matter decreases were found in the left inferior longitudinal fasciculi (ILF) and the splenium of the corpus callosum. MNI coordinates, cluster volumes and *z*-scores are presented in Table 2. We also noted in CB a significant enlargement of the occipito-frontal fasciculus (FOF: 17 26 −10 extending to 22 12 32), the superior longitudinal fasciculus (SLF: −32 −36 21) and the genu of the corpus callosum (8 29 1 extending to 0 4 24).

Alterations in non-visual structures

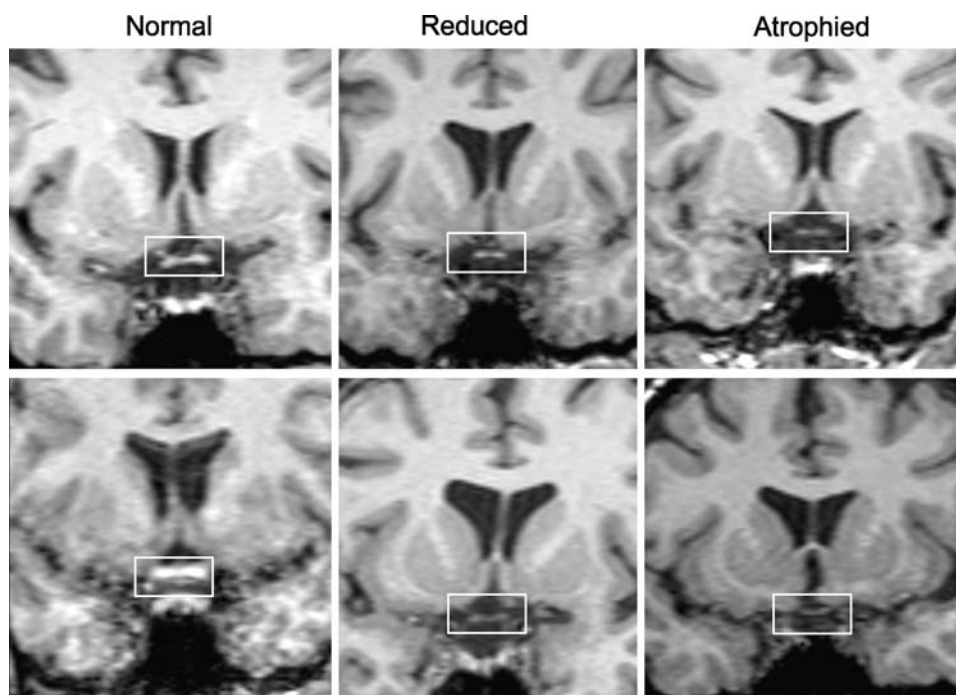
Significant volume reductions were also observed in parts of the extrapyramidal motor system, such as the caudate and lenticular nuclei, the posterior hippocampi, the fornix, the right superior frontal gyrus, the right inferior temporal gyrus, the right lateral orbital cortex (area 12L) and the

right posterior insular cortex. However, no alterations were found neither in primary sensory and motor cortices nor in the cortico-spinal tracts.

Discussion

We here report volume reductions over the entire visual system in congenitally blind subjects. Blind subjects also showed a significantly smaller total GM volume compared to NS. It is known that prematurely born individuals may show a reduced brain volume (Isaacs et al. 2004). Since four of our CB subjects were preterms, we also calculated GM and WM for preterms and at-term blind subjects separately. The results showed a trend for larger total GM (618 ± 68 vs 665 ± 68 for respective preterms and at-terms) and WM (386 ± 45 vs 434 ± 66 for respective preterms and at-terms) reductions in the preterms. However, when comparing the remaining eight CB with the SC, the significance of the differences in the total tissue content between both groups were not altered ($P > 0.05$; two-tailed *t*-test for WM and GM). Moreover, we did not observe any effect of preterm birth on the volumes of the ROIs in visual-cortex described in Fig. 2b. Furthermore, the effect of global grey (or white) matter content was singled out in the GLM analysis. We are therefore confident that the effect of preterm birth is negligible in our data.

Fig. 3 Examples of T1-weighted MRI coronal sections at the optic chiasm level in CB. *CB normal* congenitally blind with a normal optic chiasm, *CB reduced* congenitally blind with a significantly reduced but clearly identifiable optic chiasm, and *CB atrophied* congenitally blind with a heavily reduced optic chiasm with some residual fragments. The chiasmatic region has been enlarged (boxed region)



This is the first study to show that the entire occipital lobe, including BA17/18 and higher extrastriate areas are affected along with their afferent target thalamic nuclei, the pulvinar and the dLGN. Volume reductions in the visual cortex were massive, reaching a 25% reduction in area 17. Despite this massive reduction in volume, the occipital cortex remains functionally active as shown in many functional brain imaging studies (Noppeney 2007; Ptito and Kupers 2005). Not unexpectedly, the primary visual cortex was significantly more affected than the extrastriate cortices. This is likely due to the fact that the major input to the striate cortex originates in the dLGN, which no longer receives visual information from the atrophied optic nerves, optic chiasm and optic radiations. In contrast, associative visual areas also receive a larger input from polymodal association areas. The optic chiasm was absent or severely atrophied in the majority of our blind subjects. Interestingly, a normal appearing optic chiasm was found in two of our CB subjects. Atrophy of the optic chiasm was also reported in the other neuroanatomical studies of the blind's brain (see Table 3) and is in line with post-mortem analysis of the brain of an anophthalmic human subject (Brunquell et al 1984) showing absence of the optic nerves, the optic chiasm and the optic tract, and a thinner striate cortex. We also observed a reduction in the ILF, a fiber bundle, which connects the occipital cortex with the temporal lobe. The ILF arises in extrastriate visual association areas and projects to lateral and medial anterior temporal regions. This pathway is involved in several visual functions and lesions of it may induce visual agnosia, prosopagnosia and disturbances in visual recent memory (Tusa and Ungerleider

1985; Catani et al. 2003). Our finding of a reduced ILF is in line with a recent study showing a functional disconnection between the occipital and the temporal multisensory cortices (Liu et al. 2007). In agreement with earlier results (Shimony et al. 2005; Yu et al. 2007), we also noted white matter decreases in the posterior part of the corpus callosum, which links the two visual cortices and is implicated in the interhemispheric transfer of visual information (Ptito 2003).

We also observed grey matter reductions in the posterior hippocampus (bilaterally), the right inferior temporal gyrus and the right lateral orbital cortex. The volume reduction in the hippocampus confirms our earlier finding of reduced posterior hippocampus in a smaller group of early blind subjects (Chebat et al. 2007). The inferior temporal cortex is part of the ventral stream, which is involved in visual object recognition. Studies in the macaque monkey (Carmichael and Price 1995) have shown that the inferior temporal cortex projects to area 12L in the orbital cortex, which also shows atrophy in the current study.

Comparison with other studies

In this study, we found more widespread alterations in the visual system compared to the earlier reports. Table 3 summarizes the key findings of GM and WM changes in the visual system observed in this and the other published studies. We observed a massive reduction in primary visual cortex, bilaterally. This is in contrast with the results by Breitenseher et al. (1998) and Shimony et al. (2005), who did not report any grey matter changes in occipital cortex of

Table 3 Atrophy (\downarrow) in white and grey matter of the visual system in the blind as reported in this report and other published reports

	N	Blindness	Methodology	White matter changes					Grey matter changes				
				Optic nerve	Chiasm	Optic rad.	ILF	SCC	LGN	Pulvinar	BA 17	BA 18/19	Area MT
Breitenseher et al. (1998)	12	CB	Visual inspection	\downarrow	\downarrow	\downarrow	–	–	–	–	–	–	–
Noppeney et al. (2005)	11	CB + LB	VBM	\downarrow	\downarrow	\downarrow	–	–	–	–	\downarrow	\downarrow	–
Shimony et al. (2005)	5	CB	DTI/DTT	\downarrow	\downarrow	\downarrow	–	\downarrow	–	–	–	–	–
Pan et al. (2007)	14	CB + LB	VBM	\downarrow	\downarrow	\downarrow	–	–	–	–	\downarrow	\downarrow	–
This study	12	CB	VBM	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow	\downarrow

CB congenitally blind, LB late blind, DTI diffusion tensor imaging, DTT diffusion tensor tractography, SCC splenium corpus callosum, ILF inferior longitudinal fasciculus

blind subjects. This may be due to the methods used to detect such changes in these studies (resp. visual inspection of MRIs and DTI/DTT). In line with our findings, a recent VBM study in a group of 14 perinatally blind subjects also reported a large reduction in area V1/V2 (Pan et al. 2007). In contrast with our study, these authors did not report changes in associative visual areas. Although there is a large inter-study variability in GM changes, all studies concur on WM atrophy in the afferent pathways to striate cortex.

How to explain these differences? An important difference with other studies is that we used a homogeneous and significantly larger sample of congenitally blind subjects who never had any visual experience, whatsoever. In Noppeney et al.'s study (2005), more than half of the early blind subjects had visual experiences early in life; whereas in the study of Shimony et al. (2005), two out of the five CB subjects had remaining light sensitivity. This may have increased variability in their findings, reducing the likelihood to detect alterations reaching statistical significance. The use of different methodological approaches (VBM, DTI vs functional connectivity in the resting brain) may also be responsible for the variability in results.

Functional implications

Despite the large volume reductions observed in the primary visual cortex of the blind, brain imaging studies have shown a supra-normal activation of the occipital cortex at rest (De Volder et al. 1997) and in tasks involving auditory and somatosensory inputs (reviewed in Merabet et al. 2005; Sathian 2005; Sadato 2005; Ptito and Kupers 2005). This suggests that sensory input plays a large role in the organization of the neocortex, as cortical territories normally involved in visual processing are invaded by auditory and somatosensory axons, resulting in “extended” auditory and somatosensory areas (Hyvärinen et al. 1981; Kupers et al. 2006). Cross-connections between low-level cortical areas, including V1, A1 and S1, have been described in the normal brain (Zhou and Fuster 1996; Falchier et al. 2002;

Rockland and Ojima 2003) and neuronal activity was recorded in the monkey auditory cortex in response to somatic stimuli in monkeys (Schroeder et al. 2001; Fu et al. 2003). Cross-modal responses were also recorded in the auditory and visual cortices of human subjects through brain imaging techniques (reviewed in Foxe and Schroeder 2005) or direct intracranial recordings (Molholm et al. 2006). These cross-modal interactions between primary cortices and the consequent multisensory interactions might explain the activation of the occipital lobe in the congenitally blind.

Possible anatomical pathways

Two possible anatomical pathways have been proposed for processing of non-visual information by the visual cortex of the blind. One involves the formation of direct thalamocortical connections to the visual cortex and the other, the use of cortico-cortical connections from the somatosensory to the visual cortex. Arguments in support of the first pathway are based on results obtained in “rewired” animals (reviewed in Ptito and Desgents 2006). It is possible to induce, by lesioning central retinal targets, the formation of new and permanent retinofugal projections into non-visual thalamic sites such as the auditory (Frost 1981; Ptito et al. 2001) or the somatosensory nuclei (Frost 1981). These surgically induced retinal projections are retinotopically organized and make functional synapses (Metin and Frost 1989). Neurons in the somatosensory cortex of animals with ectopic retinal projections have visual response properties similar to those of neurons in the primary visual cortex of normal animals (Frost and Métin 1985; Metin and Frost 1989). Ferrets that have retinofugal projections to the auditory thalamus but no visual cortex appear to perceive light stimuli as visual (Von Melchner et al. 2000). The question concerning the parallel between a different brain organization (produced by lesions) and a behavioral recovery is still debated, although recent experiments, both in rewired ferrets and hamsters, seem to indicate a large

degree of recovery in visual functions (reviewed in Ptito et al. 2001). For example, hamsters with robust and permanent projections to the auditory thalamus nucleus (medial geniculate nucleus, MGB) and no visual system exhibit visual responses in their auditory cortex. Single neurons respond to visual stimuli and some of them respond equally well to auditory and visual stimuli. Moreover, those cells that responded to visual stimuli had receptive field properties similar to those obtained from cells in the visual cortex of normal hamsters. At the behavioral level, rewired hamsters can learn visual discrimination tasks as well as normal ones and a lesion of the auditory cortex abolishes this function (Frost et al. 2000). In fact, rewired hamsters with auditory cortex lesions exhibit cortical blindness similar to non-rewired hamsters with visual cortex lesions. Although these animal data provide evidence for the development of aberrant new and functional projections, it has yet to be confirmed in humans. Some indirect evidence in support of this hypothesis comes from a recent functional connectivity study in early blind individuals (Liu et al. 2007) that reported increased functional connectivities between the thalamus and visual cortical areas.

According to the second hypothesis, non-visual information reaches the occipital cortex via existing cortico-cortical pathways. We previously showed that functional connectivity between the dorsal intraparietal sulcal area and the cuneus is significantly increased in blind (but not control) subjects trained with the tongue display unit (TDU), a sensory substitution device that uses electrotactile stimulation of the tongue as entry to the brain to resolve visual discrimination tasks (Ptito et al. 2005). Moreover, somatosensory evoked potentials induced by electrical stimulation of the tongue after training with the TDU showed, in addition to the short latency (13–18 ms), N1–P1 complex over the parietal cortex, a second peak over the occipital cortex. This peak occurred with a latency of around 48–60 ms, suggesting a mediation by a cortico-cortical pathway (Kupers et al. 2006). Additional evidence for increased connectivity between parietal and visual cortex comes from the report that TMS of the primary somatosensory cortex induces a significant blood flow increase in the occipital cortex in congenitally blind, but not in control subjects (Wittenberg et al. 2004). Finally, the DTI results by Shimony et al. (2005) showed atrophy of the geniculocortical tract but preservation of connections between visual cortex and prefrontal and temporal cortices in blind subjects.

Conclusion

The absence of visual input in congenital blindness leads to atrophy in various components of the afferent and efferent visual pathways as schematized in Fig. 4. Although largely

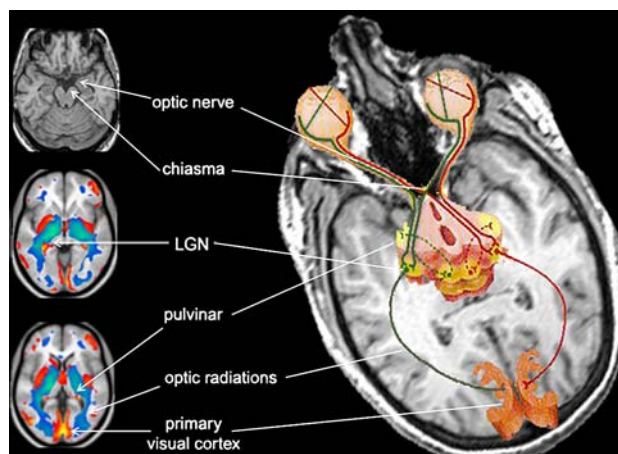


Fig. 4 Schematic representation summarizing the atrophied components (grey and white matter) of the visual system in congenitally blind subjects

reduced in volume, the visual cortex shows functional activity as measured by a variety of brain imaging techniques, suggesting the possible contribution of existing thalamocortical (Liu et al. 2007) and cortico-cortical (Shimony et al. 2005) connections in cross-modal plasticity in the congenitally blind.

Acknowledgments This work is supported by grants from the Harland Sanders Foundation (MP) and the Lundbeck Foundation (RK).

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