Increased Visual Cortical Thickness in Sight-Recovery Individuals

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Abstract: Individuals who are born blind due to dense bilateral cataracts and who later regain vision due to cataract surgery provide a unique model to evaluate the effect of early sensory experience in humans. In recent years, several studies have started to assess the *functional* consequences of early visual deprivation in these individuals, revealing a number of behavioral impairments in visual and multisensory functions. In contrast, the extent to which a transient period of congenital visual deprivation impacts brain *structure* has not yet been investigated. The present study investigated this by assessing cortical thickness of occipital areas in a group of six cataract-reversal individuals and a group of six age-matched normally sighted controls. This analysis revealed higher cortical thickness in cataract-reversal individuals in the left calcarine sulcus, in the superior occipital gyrus and in the transverse occipital sulcus bilaterally. In addition, occipital cortical thickness correlated negatively with behavioral performance in an audio-visual task for which visual input was critical, and positively with behavioral performance in auditory tasks. Together, these results underscore the critical role of early sensory experience in shaping brain structure and suggest that increased occipital cortical thickness, while potentially compensatory for auditory sensory processing, might be maladaptive for visual recovery in cases of sight restoration. *Hum Brain Mapp* 36:5265–5274, 2015. © 2015 Wiley Periodicals, Inc.

Key words: cortical thickness; visual deprivation; sight recovery

INTRODUCTION

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The critical role of early sensory experience in shaping brain and behavior in humans has been increasingly demonstrated in recent years. Several studies have documented impairments in a number of visual and multisensory processes in individuals who were born blind due to dense bilateral cataracts and who later regained patterned vision after cataract surgery. For example, cataract-reversal individuals exhibit impairments in global motion perception [Hadad et al., 2012], detection of illusory contours [Putzar et al., 2007a], and configural face processing [Robbins et al., 2010]. Moreover, cataract-reversal individuals fail to show multisensory facilitation during the audio-visual presentation of

speech stimuli with low signal-to-noise ratios [Putzar et al., 2007b], and they exhibit significantly less cross-modal interference than normally sighted controls when auditory and visual stimuli provide conflicting or interfering signals [Putzar et al., 2007b, 2010a].

Recent neuroimaging studies have started to investigate the effect of a transient period of congenital visual deprivation on the neural bases of visual, auditory, and multisensory processing. These studies have shown that cataract-reversal individuals, unlike normally sighted controls, do not exhibit lip-reading-related activation in auditory and multisensory superior temporal areas [Putzar et al., 2010b]. Furthermore, cataract-reversal individuals were recently shown to exhibit reduced activation, relative to normally sighted controls, in regions involved in face processing during passive viewing of faces, whereas—in line with recent event-related potential studies [Röder et al., 2013]—cataract-reversal individuals, but not normally sighted controls, activated regions typically involved in face processing during non-face object processing [Grady et al., 2014]. Transient congenital visual deprivation additionally appears to affect the neural bases of auditory processing, as typically visual motion-selective middle temporal (MT) area was shown to respond to both visual and auditory motion in patient M. S., who was born blind as a result of retinopathy of prematurity and cataracts and whose vision was partially restored after cataract removal in the right eye at age 43 years [Saenz et al., 2008]. Finally, an effect of transient congenital visual deprivation on the neural bases of multisensory processing was recently demonstrated, as cataract-reversal individuals, unlike normally sighted controls, did not show multisensory enhancements in auditory and multisensory regions during audio–visual speech processing, but instead seemed to suppress visual cortical processing during audio–visual stimulation [Guerreiro et al., 2015].

Despite the increasing number of studies assessing the functional consequences of a transient period of congenital visual deprivation in humans [for reviews, see Lewkowicz and Röder, 2012; Maurer and Lewis, 2013], the extent to which transient congenital visual deprivation affects brain structure has not yet been investigated. Studies conducted in permanently blind individuals—in addition to providing extensive evidence for functional brain reorganization [e.g., Renier et al., 2010; Striem-Amit et al., 2012]—have recently started to provide evidence for structural brain reorganization as a consequence of congenital or early-onset blindness, with the most consistent finding being an increased cortical thickness in occipital areas, including the calcarine sulcus [Anurova et al., 2015; Bridge et al., 2009; Jiang et al., 2009; Park et al., 2009; Qin et al., 2013], cuneus [Anurova et al., 2015; Qin et al., 2013], lingual gyrus [Anurova et al., 2015; Jiang et al., 2009; Park et al., 2009; Qin et al., 2013; Voss and Zatorre, 2012], and lateral occipital cortex [Anurova et al., 2015; Park et al., 2009; Qin et al., 2013; Voss and Zatorre, 2012]. These findings have been interpreted as reflecting a disruption of synaptic

pruning—the process occurring in the first years of life and by which weaker neural connections are eliminated—in the absence of developmental vision [e.g., Jiang et al., 2009; Park et al., 2009]. Furthermore, the covariation of cortical thickness in the occipital cortex and cortical thickness in frontal and parietal visual-related areas (i.e., frontal and supplementary eye fields, inferior parietal lobule) was shown to be reduced in a group of individuals with congenital or early-onset blindness relative to sighted controls [Voss and Zatorre, 2015]. This finding was interpreted as evidence for a decoupling of the deafferented occipital “visual” areas from other, non-occipital visual areas—and thus for neuroanatomical changes at the network level.

Recently, some of these morphological features have been linked to differences in behavioral performance, as well as to differences in brain function, in blind individuals. For example, Voss and Zatorre [2012] showed that the performance of individuals with congenital or early-onset blindness in auditory tasks was positively correlated with cortical thickness in occipital regions, suggesting that increased occipital cortical thickness in these individuals reflects adaptive compensatory plasticity. More recently, Voss and Zatorre [2015] found that the performance of individuals with congenital or early onset blindness in auditory tasks was predicted by the strength of the covariance between cortical thickness in the occipital cortex and cortical thickness in the intraparietal sulcus—an area in which cortical thickness had previously been shown to be associated with performance of sighted individuals in the employed auditory tasks [Foster and Zatorre, 2010]. With regard to the relationship between cortical thickness and brain function, Anurova et al. [2015] reported that functional activation of areas that are critical for behavioral task performance (i.e., auditory areas for auditory processing in sighted controls, visual areas for auditory processing in individuals with congenital or early-onset blindness) was negatively correlated with cortical thickness. These authors suggested that synaptic pruning increases the selectivity and effectiveness of synaptic activity, resulting in a stronger activation in thinner cortical areas.

The main goal of the present study was to investigate the effect of transient congenital visual deprivation in shaping brain structure. In other words, this study sought to explore whether cataract-reversal individuals exhibit changes in cortical thickness akin to those reported in congenitally blind individuals—as would be expected if such structural changes are brought about by a disruption of synaptic pruning in the absence of vision in the first months after birth—or whether, in contrast, cortical thickness is either not altered or can be reset to normally sighted levels after sight restoration. An additional goal of this study was to explore whether differences in cortical thickness—if any—might be associated with the behavioral impairments in visual and multisensory processing observed in cataract-reversal individuals [e.g., Putzar et al., 2007b].

METHOD

Participants

Six individuals with history of dense bilateral congenital cataracts (aged 23–45 years, $M = 32.7$, $SD = 8.5$, 3 females) and six normally sighted individuals matched for age and years of education (aged 18–45 years, $M = 31.8$, $SD = 10.0$, 4 females) were included in this study. In the group of individuals with history of cataracts, cataract surgery took place between the ages of 5 and 24 months ($M = 14.5$, $SD = 8.6$). All participants were right-handed and reported normal hearing. In the group of cataract-reversal patients, visual acuity ranged from 20/50 to 20/200, with a mean of 20/70. Besides aphakia following cataract-removal surgery, other visual impairments in the group of cataract-reversal patients included nystagmus (all cases), impaired stereo vision (all cases), esotropia (three cases), microcornea (one case), and treated glaucoma (one case). Normally sighted controls had normal or corrected-to-normal visual acuity. The study was approved by a local ethics committee (Ärztchamber Hamburg, Nr. 2502) and written informed consent was obtained from each participant before testing.

Behavioral Tasks

The behavioral data used in the present study are taken from an audio–visual speech paradigm in the same individuals, which is described in greater detail elsewhere [see Putzar et al., 2007b]. Participants performed a 1-back task, whereby they had to indicate as accurately as possible whether the word presented in the current trial was the same or not as the one presented in the previous trial. The stimuli consisted of video clips showing lip movements but no speech sounds (henceforth, visual task), no lip movements but speech sounds (henceforth, auditory task), and both lip movements and speech sounds (henceforth, audio–visual task). The signal-to-noise ratio (SNR) of the audio track was varied by adding multi-speaker babble, so that the auditory stimuli could be presented at high SNR (i.e., +16.1, in both the auditory task and in the audio–visual task) or at low SNR (i.e., –2 in the auditory task, and –7.1 in the audio–visual task). The different SNR levels were chosen on the basis of a pre-study, as those that allowed participants to correctly identify and repeat the word in average on 20% (i.e., low SNR) and 95% (i.e., high SNR) of the trials.

Image Acquisition

Participants underwent magnetic resonance imaging on a 3 T Siemens Magnetom Trio scanner (Erlangen, Germany) equipped with a standard head coil at the University Medical Center Hamburg-Eppendorf. Anatomical T1-weighted images covering the whole brain were obtained using a 3D-FLASH sequence (repetition time = 15 ms; echo time = 4.92 ms; flip angle = 25°; 192 sagittal slices; voxel dimensions = 1 mm × 1 mm × 1 mm; matrix size = 256 × 256).

Image Processing and Analysis

Image processing was performed using BrainVoyager QX 2.8 (Brain Innovation, Maastricht, The Netherlands). T1-weighted images were initially corrected for inhomogeneities, and the brain was segmented from the surrounding head tissue. Subsequently, these data were transformed to standard Talairach space and resampled to 0.5 mm isovoxels. Subcortical structures were removed using a mask that was manually adjusted for each participant, and tissue contrast and homogeneity were enhanced using a sigma filter. After these initial preparatory steps, the white matter–gray matter boundary and the gray matter–cerebrospinal fluid boundary were automatically segmented and then polished, by calculating a magnitude map based on the computed gradient maps of the binary segmentation results. The resulting data were visually inspected and manual corrections were made where necessary on an individual subject basis to ensure that the gray matter was properly segmented, after which cortical thickness volume maps were calculated for each participant using the Laplace method [Jones et al., 2000].

Cortex-based alignment was used to reduce the effect of anatomical variability and to improve the spatial correspondence of cortical areas across individuals [Fischl et al., 1999]. Specifically, the cortical surface reconstruction of each participant's brain hemisphere was aligned to a selected target brain—the atlas brain provided by BrainVoyager QX—using curvature information reflecting the gyral/sulcal folding pattern, after which cortical thickness surface maps were calculated for each participant's brain hemisphere.

Statistical Analysis

In order to increase statistical power, we used a region of interest (ROI) approach whereby we compared average thickness values from distinct occipital cortical regions between cataract-reversal individuals and normally sighted controls. The selected ROIs included the calcarine sulcus, cuneus, and lingual gyrus on the medial side of the occipital lobe (Fig. 1, upper panel), and the inferior occipital gyrus, middle occipital gyrus, superior occipital gyrus, and transverse occipital sulcus on the lateral surface of the occipital lobe (Fig. 1, lower panel). These ROIs were automatically labeled for each participant after aligning the cortical surface reconstruction of each participant's hemisphere to the atlas brain provided by BrainVoyager QX. This procedure enables an accurate remapping of predefined ROIs from the atlas brain provided by BrainVoyager QX to each individual participant's cortex, by making use of the cortical curvature information of the individual and the atlas brain.

Individual cortical thickness values were extracted from each ROI and submitted to a repeated measures ANOVA with ROI (7 levels: calcarine sulcus, cuneus, lingual gyrus, inferior occipital gyrus, middle occipital gyrus, superior occipital gyrus, transverse occipital sulcus) and hemisphere (2 levels: left, right) as within-group factors, and group

Figure 1.

Regions of interest on the medial surface of the occipital lobe (upper panel) and on the lateral surface of the occipital lobe (lower panel). CUN = cuneus; CAS = calcarine sulcus; LING = lingual gyrus; TOS = transverse occipital sulcus; SOG = superior occipital gyrus; MOG = middle occipital gyrus; IOG = inferior occipital gyrus.

(2 levels: cataract-reversal individuals, normally sighted controls) as a between-group factor. Significant higher-order interactions were followed up by appropriate post hoc repeated measures ANOVA.

RESULTS

Cortical Thickness

Table I presents the mean cortical thickness of each occipital area in cataract-reversal individuals and normally sighted controls.

There was a main effect of group, $F(1, 10) = 8.87$, $P = 0.014$, suggesting that overall cortical thickness was higher in cataract-reversal individuals ($M = 3.00$ mm, $SD = 0.38$) than in normally sighted controls ($M = 2.76$ mm, $SD = 0.39$). The main effect of ROI was likewise significant, $F(6, 60) = 28.88$, $P < 0.001$, indicating that cortical thickness differed across ROIs. Importantly, group interacted with ROI, $F(6, 60) = 2.49$, $P = 0.032$, revealing that group differences in cortical thickness differed across ROIs.

There was a ROI $\times$ Hemisphere interaction, $F(6, 10) = 7.71$, $P < 0.001$, but no ROI $\times$ Hemisphere $\times$ Group interaction, $F(6, 10) = 1.14$, $P = 0.348$, indicating that hemispheric differences in cortical thickness differed across ROIs, but not between groups.

Because the ROI $\times$ Group interaction and the ROI $\times$ Hemisphere interaction were both significant, the cortical thickness data of each ROI were further analyzed with repeated measures ANOVA with hemisphere (2 levels: left, right) as a within-group factor and group (2 levels: cataract-reversal individuals, normally sighted controls) as a between-group factor (Table II). In the following, we report the results for those areas in which significant differences between groups were found.

Calcarine sulcus

There was no main effect of group, $F(1, 10) = 0.62$, $P = 0.449$, but there was a significant interaction between group and hemisphere, $F(1, 10) = 9.88$, $P = 0.010$. Planned within-group comparisons (two-tailed, paired-sample t -tests) revealed that the right calcarine sulcus was thicker than the left calcarine sulcus in the group of normally sighted controls, $t(5) = 3.83$, $P = 0.012$, whereas cortical thickness in the calcarine sulcus did not differ between hemispheres in the group of cataract-reversal individuals, $t(5) = 0.89$, $P = 0.412$. Planned between-groups comparisons (two-tailed, independent-sample t -tests) revealed that the left calcarine sulcus was thicker in cataract-reversal individuals than in normally sighted controls, $t(10) = 3.13$, $P = 0.011$, whereas the right calcarine sulcus did not differ between groups, $t(10) = 1.00$, $P = 0.342$.

TABLE I. Mean cortical thickness (in mm) and standard deviations (in parentheses) as a function of group, region of interest, and hemisphere

Region of interest	Left hemisphere		Right hemisphere	
	Normally sighted controls	Cataract-reversal individuals	Normally sighted controls	Cataract-reversal individuals
Calcarine sulcus	2.51 (0.24)	2.85 (0.12)	2.91 (0.25)	2.74 (0.32)
Cuneus	2.34 (0.11)	2.59 (0.26)	2.63 (0.50)	2.66 (0.31)
Lingual gyrus	2.93 (0.16)	3.12 (0.13)	3.00 (0.20)	3.06 (0.22)
Inferior occipital gyrus	3.47 (0.36)	3.65 (0.24)	3.05 (0.30)	3.19 (0.16)
Middle occipital gyrus	3.02 (0.34)	3.33 (0.44)	2.73 (0.16)	2.93 (0.21)
Superior occipital gyrus	2.45 (0.23)	3.03 (0.49)	2.52 (0.14)	2.82 (0.25)
Transverse occipital sulcus	2.68 (0.19)	3.15 (0.34)	2.40 (0.16)	2.94 (0.23)

Significant differences are indicated in boldface.

Superior occipital gyrus

There was a main effect of group, $F(1, 10) = 14.85$, $P = 0.003$, but no interaction between group and hemisphere, $F(1, 10) = 1.02$, $P = 0.336$, indicating that the superior occipital gyrus was significantly thicker in cataract-reversal individuals than in normally sighted controls in both hemispheres.

Transverse occipital sulcus

There was a main effect of group, $F(1, 10) = 18.62$, $P = 0.002$, but no interaction between group and hemisphere, $F(1, 10) = 0.17$, $P = 0.693$, indicating that the transverse occipital sulcus was significantly thicker in cataract-reversal individuals than in normally sighted controls in both hemispheres.

Behavioral Results

With a larger sample, Putzar et al. [2007b, 2010a] had reported that cataract-reversal individuals performed worse than normally sighted controls in the visual (i.e., lip-reading) task, as well as in the audio-visual task with low SNR. In contrast, cataract-reversal individuals did not differ from normally sighted controls in the audio-visual task with high SNR, nor in the auditory tasks regardless of SNR [Putzar et al., 2007b].

In the present study, we confirmed this pattern of results with a sub-set of the original sample: Planned comparisons (one-tailed, independent-sample t -tests), aimed at testing the directional hypothesis that cataract-reversal individuals perform worse than normally sighted controls in those conditions for which visual input is critical (i.e., visual task and audio-visual task with low SNR), revealed that cataract-reversal individuals responded less accurately ($M = 74.2\%$, $SD = 8.0$) than normally sighted controls ($M = 87.6\%$, $SD = 1.5$) in the visual task, $t(5.42) = 4.01$, $P = 0.005$, as well as less accurately ($M = 59.3\%$, $SD = 26.4$) than normally sighted controls ($M = 86.2\%$, $SD = 15.0$) in the audio-visual task with low SNR, $t(9) = 2.01$, $P = 0.038$. No other differences reached significance ($P_s > 0.050$). Please note that behavioral data were not available for one normally sighted control participant because of technical problems with the response device.

Correlations

Cortical thickness and behavioral performance

Cataract-reversal individuals performed worse than normally sighted controls in the visual (i.e., lip-reading) task, as well as in the audio-visual task with low SNR [see Putzar et al., 2007b, 2010a]. At the same time, cataract-reversal individuals exhibited thicker cortex in occipital areas. This raises

TABLE II. Summary of analyses of variance for each region of interest

Region of interest	Group		Hemisphere		Hemisphere × Group	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Calcarine sulcus	0.62	0.449	3.14	0.107	9.88	0.010
Cuneus	1.00	0.340	1.98	0.190	0.84	0.382
Lingual gyrus	2.51	0.144	0.02	0.905	1.02	0.336
Inferior occipital gyrus	1.31	0.280	31.73	0.000	0.11	0.752
Middle occipital gyrus	2.67	0.134	17.35	0.002	0.36	0.560
Superior occipital gyrus	14.85	0.003	0.24	0.636	1.02	0.336
Transverse occipital sulcus	18.62	0.002	9.85	0.011	0.17	0.693

Figure 2.

Occipital regions showing a negative correlation between cortical thickness and behavioral performance of cataract-reversal individuals in the audio-visual task with low signal-to-noise ratio.

the possibility that the behavioral decrements observed in cataract-reversal individuals are associated with increased occipital cortical thickness. In order to explore this directional hypothesis, we performed one-tailed Spearman's rank correlations between cortical thickness of occipital brain areas and behavioral performance (i.e., accuracy) in the visual (i.e., lip-reading) task and in the audio-visual task with low SNR. Although no significant correlations emerged between occipital cortical thickness and behavioral performance of cataract-reversal individuals in the visual (i.e., lip-reading) task ($P_s > 0.050$), there were significant negative correlations between behavioral performance of cataract-reversal individuals in the audio-visual task with low SNR and cortical thickness in several occipital areas—namely, the right inferior occipital gyrus, $r_s = -0.84, P = 0.018$, the right superior occipital gyrus, $r_s = -0.75, P = 0.042$, the right calcarine sulcus, $r_s = -0.75, P = .042$, and the left cuneus, $r_s = -0.75, P = 0.042$ (Fig. 2)—, suggesting that the thicker the occipital cortex, the lower the behavioral performance of

cataract-reversal individuals in the audio-visual task with low SNR. Worth noting, none of these correlations were significant in the group of normally sighted controls ($P_s > 0.050$), suggesting that the relationship between increased occipital cortical thickness and behavioral impairments during audio-visual processing is unique to cataract-reversal individuals.

Increased occipital cortical thickness has been associated with superior auditory abilities in the individuals with congenital or early-onset blindness [Voss and Zatorre, 2012], raising the possibility that increased occipital cortical thickness might be positively associated with auditory performance in cataract-reversal individuals. In order to test this directional hypothesis, we performed one-tailed Spearman's rank correlations between occipital cortical thickness and behavioral performance of cataract-reversal individuals in the auditory tasks (collapsed across SNR levels). This analysis revealed a significant positive correlation between behavioral performance of cataract-reversal

Figure 3.

Occipital regions showing a positive correlation between cortical thickness and behavioral performance in cataract-reversal individuals in the auditory tasks.

individuals in the auditory tasks and cortical thickness in the left calcarine sulcus, $r_s = 0.81$, $P = 0.025$, as well as in the left middle occipital gyrus, $r_s = 0.75$, $P = 0.042$ (Fig. 3), suggesting that the thicker the occipital cortex in these areas, the higher the behavioral performance of cataract-reversal individuals during auditory processing. Again, none of these correlations was significant in the group of normally sighted controls ($P_s > 0.050$), indicating that the relationship between increased occipital cortical thickness and enhanced auditory performance is unique to cataract-reversal individuals.

Cortical thickness and history of visual functioning

In order to explore the relationship between occipital cortical thickness and duration of visual deprivation (i.e., time from birth until cataract surgery), as well as the relationship between occipital cortical thickness and duration of sight recovery (i.e., time from cataract surgery), we performed partial correlations between these variables, while controlling for the effects of age, in the group of cataract-reversal individuals. These analyses revealed no significant correlations ($P_s > 0.050$).

Behavioral performance and history of visual functioning

In order to explore the relationship between behavioral performance and duration of visual deprivation, as well as between behavioral performance and duration of sight recovery, we performed partial correlations between these variables, while controlling for the effects of age, in the group of cataract-reversal individuals. These analyses revealed no significant correlations ($P_s > 0.050$).

DISCUSSION

The main goal of this study was to investigate the effect of transient congenital visual deprivation in shaping brain structure during development. To this end, we compared cortical thickness of occipital regions between cataract-reversal individuals and normally sighted controls. Increased cortical thickness was observed in cataract-reversal individuals relative to normally sighted controls in the left calcarine sulcus and in the superior occipital gyrus and transverse occipital sulcus bilaterally. An additional goal of this study was to explore whether occipital cortical thickness correlates with behavioral parameters in cataract-reversal individuals. To this end, we performed exploratory correlation analyses between occipital cortical thickness and behavioral performance of cataract-reversal individuals in visual, auditory, and audio-visual versions of a speech recognition paradigm that had previously been employed in the present sample [see Putzar et al., 2007b]. We found significant positive correlations between auditory performance of cataract-reversal individuals and cortical thickness in the left calcarine sulcus and in the left middle occipital gyrus. By contrast, although no correlations emerged between occipital cortical thickness and visual performance, there were significant negative correlations between performance of cataract-reversal individuals in an audio-visual speech task with low SNR [for which visual input is particularly critical, see Putzar et al., 2007b] and cortical thickness in a number of occipital areas, including the right calcarine sulcus, the left cuneus, the right inferior occipital gyrus, and the right superior occipital gyrus. In contrast, no correlations emerged between occipital cortical thickness and performance of normally sighted controls in the visual, auditory, or audio-visual versions of this speech recognition paradigm. In the following paragraphs, we discuss each of these findings separately.

The increased occipital cortical thickness observed in cataract-reversal individuals relative to normally sighted controls is in line with the results from studies conducted in the permanently blind population, which have consistently shown that congenital or early-onset blindness is associated with increased cortical thickness in occipital areas [e.g., Anurova et al., 2015; Bridge et al., 2009; Jiang et al., 2009; Park et al., 2009; Qin et al., 2013; Voss and Zatorre, 2012]. The development of the primary visual cortex in humans has been shown to involve two periods: an initial period of rapid synapse production, with the number of synapses reaching its maximum at age 8–12 months; followed by a period of extensive synaptic pruning, with the number of synapses reaching adult values by age 11 years [Huttenlocher et al., 1982]. Previous animal research has shown that synaptogenesis occurs independently of visual input, whereas synaptic pruning depends on sensory experience [e.g., Bourgeois et al., 2000]. The increased cortical thickness in occipital areas of individuals who were born blind [i.e., cataract-reversal individuals in the present study; congenitally blind individuals in prior studies, see Anurova et al., 2015; Bridge et al., 2009; Jiang et al., 2009; Park et al., 2009] relative to normally sighted controls (or late-blind individuals) suggests that congenital visual deprivation seems to arrest synaptic pruning [see also Jiang et al., 2009]. Importantly, here we extend the findings previously obtained in permanently blind individuals by showing a lack of recovery—that is, a lack of visual cortical thinning—in a group of individuals in whom visual deprivation lasted only a few months after birth (i.e., 5–24 months)—well before the end of the period of synaptic pruning [i.e., 11 years of age; Huttenlocher et al., 1982]—and who experienced a rather extended period of visual recovery (i.e., 18–43 years). Worth noting, group differences in cortical thickness were found in the left calcarine sulcus, but not in the right calcarine sulcus. Although somewhat unexpected—in that previous studies have found that individuals with congenital or early blindness show increased cortical thickness in the calcarine sulcus bilaterally relative to sighted controls [Bridge et al., 2009; Jiang et al., 2009; Park et al., 2009; Qin et al., 2013]—, similar findings have been reported elsewhere. For example, studies using volumetric techniques have observed gray matter volume differences between individuals with congenital or early-onset blindness and sighted controls to be particularly predominant in the left hemisphere [e.g., Lepore et al., 2010; Yang et al., 2014]. Most importantly, using the same analytical approach as the one used in the present study, Anurova et al. [2015] has likewise found that differences in cortical thickness between individuals with congenital or early blindness and sighted controls emerged in the left—but not right—calcarine sulcus.

An additional goal of this study was to explore whether occipital cortical thickness is associated with behavioral performance of cataract-reversal individuals during visual,

auditory, and audio-visual processing. We found that cortical thickness in the left calcarine sulcus and in the left middle occipital gyrus were positively correlated with auditory performance in the cataract-reversal group—but not in the normally sighted control group. This finding is consistent with the results obtained by Voss and Zatorre [2012], who likewise found occipital cortical thickness to be predictive of auditory performance in individuals with congenital or early-onset blindness. In contrast, we found no correlations between occipital cortical thickness and visual performance in the cataract-reversal group—but we did find significant negative correlations between performance of cataract-reversal individuals in an audio-visual task with low SNR and cortical thickness in a number of occipital areas, including the right calcarine sulcus, the left cuneus, the right inferior occipital gyrus, and the right superior occipital gyrus. Although a negative correlation would have been expected particularly between occipital cortical thickness and visual performance—rather than between occipital cortical thickness and audio-visual performance—, this may have been due to the higher variability of cataract-reversal individuals' performance in the latter task (where the percentage of correct responses varied between 23% and 83%) as compared to the former task (where the percentage of correct responses varied between 65% and 83%). At any rate, that visual processing is particularly important for performance in the audio-visual task with low SNR is suggested by the fact that this is the task in which normally sighted controls benefit the most from concurrently presented congruent visual stimuli [i.e., lip movements; see Putzar et al., 2007b]. Worth noting, most of the areas where we found negative correlations between occipital cortical thickness and audio-visual performance in the group of cataract-reversal individuals—namely, the right calcarine sulcus, the left cuneus, and the right inferior occipital gyrus—were areas in which we found no significant differences in cortical thickness between groups. This contrasts with results from studies in the blind population, which have shown increased cortical thickness in these areas in individuals with congenital or early-onset blindness as compared to sighted controls [e.g., Anurova et al., 2015; Bridge et al., 2009; Jiang et al., 2009; Park et al., 2009; Qin et al., 2013]. Thus, unlike those areas in which we did find increased cortical thickness in cataract-reversal individuals relative to sighted controls, these areas may have shown recovery (i.e., cortical thinning) in cataract-reversal individuals. The resulting variability in cortical thickness among cataract-reversal individuals, in turn, may account for why negative correlations with audio-visual performance were found primarily in such areas where no significant group differences in cortical thickness emerged. Specifically, some of the cataract-reversal individuals may have shown recovery (i.e., cortical thinning) in those areas (thus, becoming indistinguishable from normally sighted controls and, therefore, precluding group differences in cortical thickness in these

areas), with those individuals who recovered the most being those who performed the best.

A potential limitation of the present study refers to the rather low number of participants (i.e., $n = 6$ per group), which may have arguably limited our statistical power to detect significant effects in the present study. Importantly, we did find significant group differences in cortical thickness that were in line with the hypotheses based on findings in permanently blind individuals. Thus, the attained test power was sufficient to detect group differences in the present study. Furthermore, despite the small sample size, we did find significant and consistent correlations between occipital cortical thickness and behavioral performance in the group of cataract-reversal individuals. Future studies should include larger samples, if possible spanning a larger range of ages at which sight was restored, so as to increase the statistical power to detect group differences at the whole-brain level as well as to detect potential correlations between cortical thickness and duration of visual deprivation or sight recovery. For the time being, the present findings shed the first light on the effects of transient congenital sensory deprivation on brain morphology in humans—and thus on the effects of experience on structural brain development—, allowing directional hypotheses to be put forward for future studies on brain development.

CONCLUSION

In conclusion, the present study shows that cataract-reversal individuals—that is, individuals who experienced a transient period of congenital visual deprivation—exhibit increased cortical thickness in occipital areas. Furthermore, we found that occipital cortical thickness was positively associated with performance of cataract-reversal individuals in auditory tasks, but negatively associated with performance on an audio—visual task for which visual input appears to be critical [see Putzar et al., 2007b]. These findings indicate that early sensory experience plays an important role in shaping brain structure, and that structural brain changes associated with early sensory deprivation—while suggested to be adaptive in the blind brain [Voss and Zatorre, 2012]—might be maladaptive for functional recovery in cases of sight restoration.

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