Report

Current Biology

Long-Lasting Crossmodal Cortical Reorganization Triggered by Brief Postnatal Visual Deprivation

Highlights

- We tested people with congenital dense bilateral cataracts that were treated in infancy
- Short visual deprivation early in life triggers life-long crossmodal plasticity
- Cortical connections appear to mediate auditory activity in occipital regions
- Early sensory experience permanently shapes brain architecture

Authors

Olivier Collignon, Giulia Dormal, Adelaide de Heering, Franco Lepore, Terri L. Lewis, Daphne Maurer

Correspondence

olivier.collignon@unitn.it

In Brief

The study of Collignon et al. demonstrates that temporary visual deprivation early in life induces permanent auditory response in occipital regions. This study therefore highlights the crossmodal competition for brain territories happening in the early sensitive period of brain development.

Collignon et al., 2015, Current Biology *25*, 1–5
September 21, 2015
http://dx.doi.org/10.1016/j.cub.2015.07.036

CellPress

Please cite this article in press as: Collignon et al., Long-Lasting Crossmodal Cortical Reorganization Triggered by Brief Postnatal Visual Deprivation, Current Biology (2015), http://dx.doi.org/10.1016/j.cub.2015.07.036

Current Biology
Report

Long-Lasting Crossmodal Cortical Reorganization Triggered by Brief Postnatal Visual Deprivation

Olivier Collignon,[1,2,*] Giulia Dormal,[2,5] Adelaide de Heering,[3,5] Franco Lepore,[2] Terri L. Lewis,[3,4] and Daphne Maurer[3,4]
[1]Centre for Mind/Brain Science (CIMeC), University of Trento, Rovereto, TN 38068, Italy
[2]Centre de Recherche en Neuropsychologie et Cognition (CERNEC), Department of Psychology, University of Montreal, Montreal, QC H3C 3J7, Canada
[3]Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, ON L8S 4K1, Canada
[4]Department of Ophthalmology, The Hospital for Sick Children, Toronto, ON M5G 1X8, Canada
[5]Psychological Sciences Research Institute and Institute of Neuroscience, University of Louvain, 1348 Louvain-la-Neuve, Belgium
*Correspondence: olivier.collignon@unitn.it
http://dx.doi.org/10.1016/j.cub.2015.07.036

SUMMARY

Animal and human studies have demonstrated that transient visual deprivation early in life, even for a very short period, permanently alters the response properties of neurons in the visual cortex and leads to corresponding behavioral visual deficits [1–7]. While it is acknowledged that early-onset and long-standing blindness leads the occipital cortex to respond to non-visual stimulation [8, 9], it remains unknown whether a short and transient period of postnatal visual deprivation is sufficient to trigger crossmodal reorganization that persists after years of visual experience. In the present study, we characterized brain responses to auditory stimuli in 11 adults who had been deprived of all patterned vision at birth by congenital cataracts in both eyes until they were treated at 9 to 238 days of age. When compared to controls with typical visual experience, the cataract-reversal group showed enhanced auditory-driven activity in focal visual regions. A combination of dynamic causal modeling with Bayesian model selection [10] indicated that this auditory-driven activity in the occipital cortex was better explained by direct cortico-cortical connections with the primary auditory cortex than by subcortical connections. Thus, a short and transient period of visual deprivation early in life leads to enduring large-scale crossmodal reorganization of the brain circuitry typically dedicated to vision.

RESULTS AND DISCUSSION

We examined whether a short period of visual deprivation during the early sensitive period of brain development leads to enduring alterations of auditory-driven activity in occipital regions even after years of visual experience. To investigate this question, we contrasted the cerebral responses observed in cataract-reversal patients operated at an early age and in control individuals when two auditory conditions were combined (cataract > control [motion + voice]; see the Experimental Procedures). This analysis revealed two circumscribed clusters where activity was larger in the cataract-reversal than in the control group: one in the right cuneus and one in the left superior occipital gyrus /cuneus (see Figure 1 and Table S2, part A), both in the vicinity of V3d/V3a. These retinotopic regions [11] are notably involved in motion processing [11] and stereoscopic depth perception [12, 13], two abilities that are highly dependent on early binocular visual experience [13, 14] and impaired in this cohort of cataract-reversal patients [15, 16]. These regions display crossmodal responses to auditory stimulation in adults with early-acquired blindness, but not in adults with late-acquired blindness, a pattern revealing a sensitive period for crossmodal plasticity [17], perhaps related to the rapid myelinization phase of these regions in early infancy [18]. Together, these findings suggest the existence of a region-specific susceptibility to the effects of transient congenital visual deprivation on crossmodal reorganization.

We also carried out two-sample t tests (cataract > control) on condition effects ([motion > voice] and [voice > motion]) to investigate whether the reorganized occipital cortex of the cataract-reversal group showed enhanced functional selectivity for specific auditory processing [19, 20]. None of these contrasts revealed any significant effects, suggesting that the higher involvement of occipital regions for sound processing in cataract-reversal patients was not task specific (see Figure S1.4). This absence of functional preference was not caused by a lack of sensitivity of the paradigm to disclose separate brain networks for auditory motion and voice processing since a between-group conjunction analysis showed motion-selective responses in the bilateral supramarginal gyrus [21] (see also Figure S1.3 and Figure S1.6 for a focus on selective auditory motion activity in the human middle-temporal (hMT+) in both groups [22, 23]) and voice-selective responses in a widespread network of bilateral temporal areas encompassing the temporal voice area and the inferior frontal gyrus [24] (see Figure S1.3 and Table S2, parts C and D). This suggests that a short period of visual deprivation early in life triggers long-lasting auditory recruitment of occipital regions, but this crossmodal plasticity is not functionally selective as is typically observed after early and prolonged visual deprivation [19, 25–27]. Since both our auditory tasks required the participants to process the duration of the auditory stimuli, this raises the intriguing possibility that these occipital activations may relate to the processing of auditory duration.

Our study is the first one to demonstrate that a restricted period of visual deprivation early in life induces long-standing

CURBIO 12179

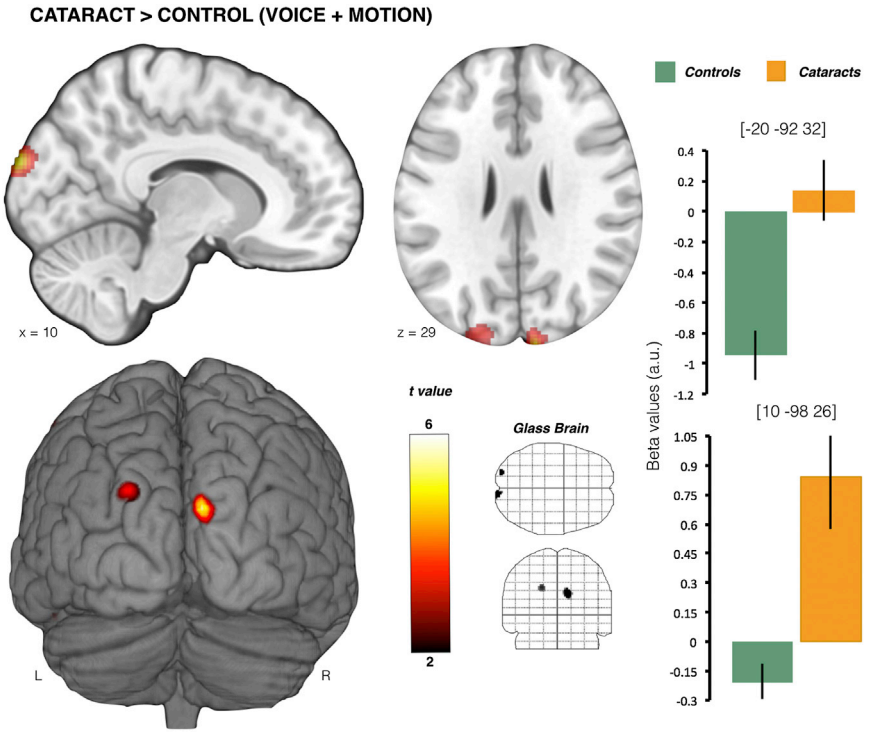

Figure 1. Crossmodal Reorganization of Occipital Regions in the Cataract-Reversal Group

Activations obtained from the contrast (cataract > control [motion + voice]) testing for regions more strongly responsive in cataract-reversal patients than in controls during global auditory processing. Graphs show the mean parameter estimates (beta values [a.u.] ± SEM) associated with the processing of sounds in controls (green) and cataract-reversal patients (orange) for the two significant peaks. The statistical parametric mapping (SPM) glass brain illustrates the spatial specificity of the observed effects. See also Figure S1 and Tables S1 and S2.

crossmodal activity in occipital regions in humans. One study conducted in monkeys that were deprived of vision during the first year of life demonstrated that the posterior parietal association cortex (BA7) loses its responsiveness to visual stimulation but responds to tactile stimulation and active somatic exploration even 1 year after restored vision [28]. Two previous studies in humans demonstrated that auditory and visual activity may co-exist in occipital regions after sight-restoration [29, 30]. However, these studies were carried out in patients who reacquired sight after a lifelong history of visual deprivation.

The auditory-driven activity observed in the occipital cortex of cataract-reversal patients is best explained by direct feed-forward connections from A1 to cuneus, rather than by subcortical connections (model 2 in Figure 2; exceedance probability of 0.74). Interestingly, similar findings were previously reported in congenitally blind subjects [17, 31]. Wiring of neural circuits during development depends on both molecular cues that guide connectivity and activity-dependent mechanisms that use patterned activation to adjust the strength and number of synaptic connections [32]. Histological studies demonstrate that exuberant projections from the auditory to the visual cortex existing in newborn kittens and macaque monkeys are gradually eliminated during the synaptic pruning phase [33–36], with only a small fraction of these projections being maintained into adulthood [37, 38]. Importantly, extrinsic connections to the occipital cortex remain in kittens deprived of vision at birth [39–41]. It is therefore possible that even a short transient period of visual deprivation early in life is sufficient to trigger the reinforcement of a significant number of direct auditory connections to the occipital cortex [8, 42]. A recent study demonstrated that cataract-reversal patients, unlike controls, exhibited lower visual cortical activity during audio-visual stimulation than during visual stimulation alone [43]. It is therefore possible that in some contexts (e.g., audio-visual stimulation), reinforced auditory-visual connections support inhibitory modulation of visual responses (see also [44]) in cataract-reversal patients that may be related to their altered audio-visual integration abilities [45, 46]. Future studies should assess whether the crossmodal auditory activations observed in this study functionally support behavior. This could be tested by using transcranial magnetic stimulation to interfere with the functioning of these regions and evaluate its detrimental effect on auditory processing, as was demonstrated previously in early blind adults [47, 48].

The existence of auditory responses in the occipital cortex of cataract-recovery patients poses crucial questions regarding how these non-visual inputs coexist or even interfere with visual functions. Support for the idea that crossmodal plasticity might interfere with the optimal resettlement of the regained sensory inputs comes from research demonstrating that the success of cochlear implants in deaf patients is inversely correlated with the amount of visual activity recorded in the auditory cortex [49–51]. It is therefore possible that auditory-driven activity in occipital regions interferes with visual processing and that individuals with the strongest crossmodal recruitment are also those with the poorest visual acuity. Our data do not support this hypothesis since the amplitude of the crossmodal responses in occipital regions was not significantly correlated (Spearman's rho) with visual scores on the Landolt-C acuity, Landolt-C contrast, vernier acuity, or letter acuity (all $p > 0.35$; see Figures S1.9A–9D). In fact, enhanced auditory activity in occipital regions was evident even in cataract-reversal patients with acuity scores within normal limits (e.g., 0.8 in letter acuity). Crossmodal activity in occipital regions also did not correlate with the duration of visual deprivation (all $p > 0.48$; see Figure S1.9E), suggesting that as little as a few weeks of visual deprivation after birth are sufficient to trigger longstanding large-scale crossmodal reorganization of occipital circuits.

Crossmodal responses to sounds in cataract-reversal subjects are unlikely to arise from reduced vision per se. First, the amplitude of auditory responses in occipital regions did not correlate with any of the visual acuity measures (see Figures S1.9A–9D).

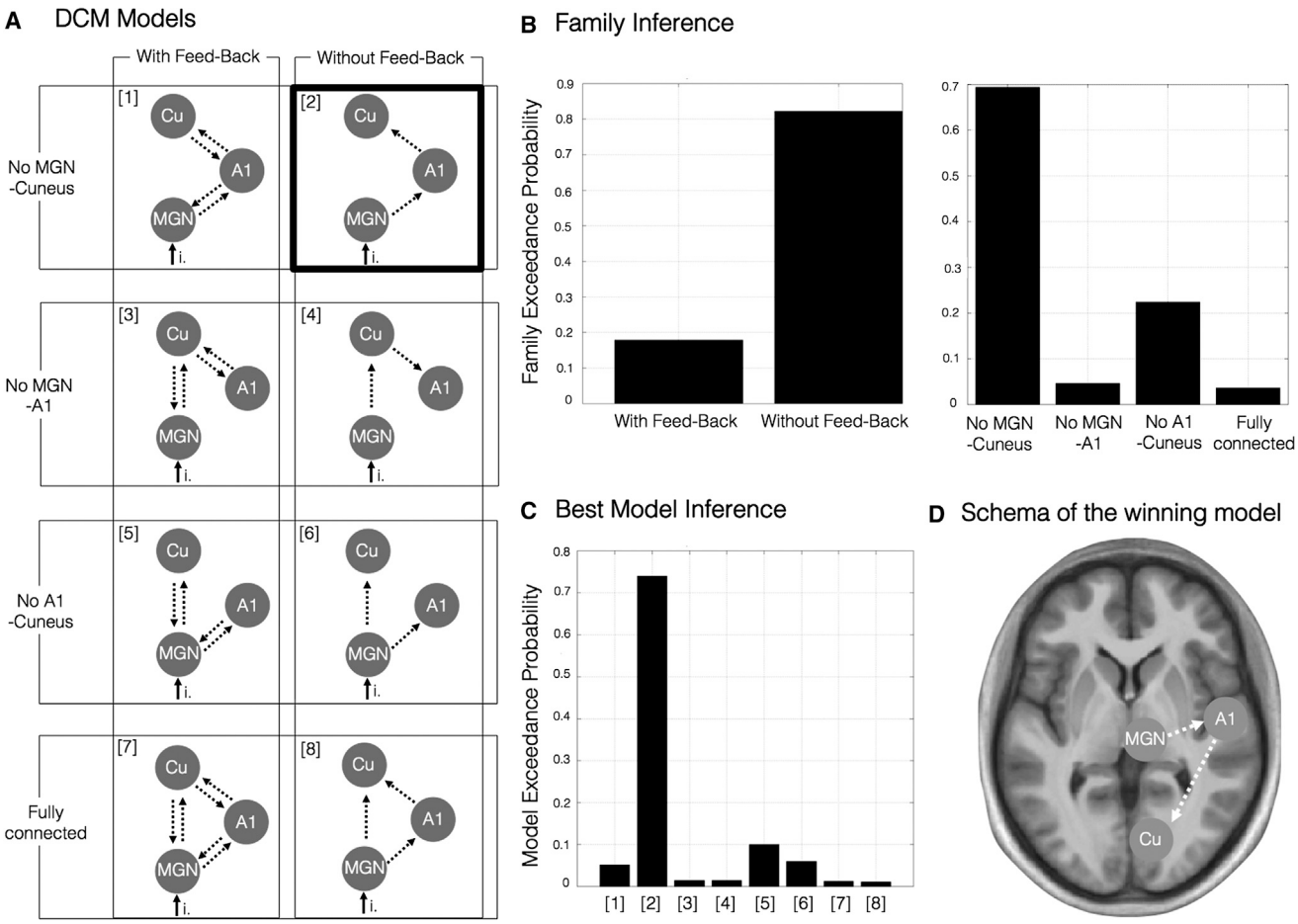

Figure 2. Dynamic Causal Modeling

(A) The eight dynamic causal models used for Bayesian model comparison. Each model receives (parameterized) subcortical input at the medial geniculate nucleus (MGN) source.

(B) Family-wise Bayesian model selection was used to establish the best neuronal network architecture in cataract-reversal patients. Families of models without feedback and without MGN-cuneus connections best explained the data.

(C) Random-effects Bayesian model selection showed that the model connecting MGN to A1 and A1 to cuneus (model 2) best fits the data in the cataract-reversal group.

(D) A schematic representation of how auditory information flows toward the occipital cortex in cataract-reversal individuals.

See also Table S1.

In fact, most of the cataract-reversal patients had nearly normal visual acuity (6 out of 11 patients have an acuity equal to or better than 20/32 in at least one eye (better, for example, than the 20/50 acuity necessary for a Canadian driving license; see Table S1) and yet showed robust auditory activity in occipital regions (see Figures S1.9A–9D). Second, if reduced vision at the time of the scan was the cause of the auditory recruitment of occipital regions, one would expect auditory recruitment also to be apparent in primary visual regions, where it was not. Finally, the regions showing auditory recruitment in the cataract-reversal patients (V3d/V3a) are nearby the regions showing specific crossmodal reorganization in early- but not late-blind adults using similar auditory tasks (here, −20, −92, 32/10, −98, 26; [17], −10, −94, 20/06, −84, 20). If late-blind people do not show auditory recruitment of these regions, it is unlikely that this phenomenon observed in cataract-reversal patients results from reduced vision per se.

In conclusion, by testing a population of adults treated in infancy for bilateral dense congenital cataracts, we demonstrate that a short period of visual deprivation at birth is sufficient to trigger enduring crossmodal reorganization in specific brain regions typically supporting vision. This enhanced auditory activity in the occipital cortex seems to be mediated by direct cortico-cortical connections between auditory and visual regions. Whether this crossmodal reorganization contributes to the impaired visual abilities observed in cataract-reversal patients remains a crucial question for future investigations [52].

EXPERIMENTAL PROCEDURES

Participants

We tested 11 adults treated for bilateral congenital cataracts within the first year of life (four females, range 18–32 years of age, mean ± SD = 24 ± 6 years) and an age-matched control group of 11 individuals with no history of visual

deprivation (three females, range 23–37 years of age, mean ± SD = 28 ± 4 years). All participants were right-handed. Two additional control participants were tested but not included in the analyses because of artifacts in the fMRI images (n = 1) or excessive head movement during the fMRI acquisition (n = 1).

Patients were included if they had been diagnosed by an ophthalmologist with dense bilateral cataracts blocking all patterned visual input until the cataracts were removed and the eyes fit with compensatory contact lenses between 9 to 238 days of age (mean = 133 days; see Table S1). Detailed inclusion and exclusion criteria for bilaterally deprived patients have been described elsewhere [53]. Since all patients tested in the current study were more than 18 years of age, all had accumulated years of visual input after treatment. On the day of testing, their corrected acuity in the better eye ranged from 20/25 to 20/125 (median = 20/32). None of the participants took medications that might affect brain function, and none had any neurological or psychiatric conditions according to self-report and medical records.

Procedures

All the procedures were approved by the research ethics boards of McMaster University, The Hospital for Sick Children in Toronto (SickKids), the Quebec Bio-Imaging Network in Montreal (QBIN), and the scientific board of QBIN. Experiments were undertaken with the understanding and signed consent of each participant.

fMRI Tasks and General Experimental Design

The fMRI acquisition procedure consisted of two auditory conditions alternating with rest periods in blocks of 16.8 s, with 15 repetitions for each condition. One condition consisted of human voices and the other of horizontally moving sounds. The two conditions were matched for low-level properties (see the Supplemental Experimental Procedures and Figure S1.1). An occasional target stimulus (either a vowel or a moving sound) lasted longer (1,400 ms) than the standard stimuli (700 ms). The task for the participant was to detect that target and press a response key with the right index finger (see behavioral performance in Figure S1.2). Details of the auditory stimuli can be found in the Supplemental Experimental Procedures.

MRI/fMRI Data Acquisition

The MRI measurements were obtained using a 3T TRIO TIM system (Siemens) equipped with a 12-channel head coil. Functional data based on the blood-oxygen-level-dependent (BOLD) signal were acquired using a multiple gradient echo-planar T2*-weighted pulse sequence using axial slice orientation with the following parameters: 2,200 ms time to repetition (TR), 30 ms echo time (ET), 90° flip angle (FA), 35 transverse slices, 3.2 mm slice thickness, 0.8 mm (25%) inter-slice gap, 192 × 192 mm^2 field of view (FoV), 64 × 64 × 35 matrix size; and 3 × 3 × 3.2 mm^3 voxel size. The three initial scans were discarded to allow for steady-state magnetization and equilibrium in image contrast. Anatomical data was acquired using a T1-weighted 3D magnetization prepared rapid acquisition gradient echo sequence (MPRAGE) with the following parameters: 1 × 1 × 1.2 mm^3 voxel size, 240 × 256 matrix size, 2,300 ms TR, 2.91 ms ET, 900 ms TI, 256 FoV, 160 slices.

fMRI Data Analyses

Details of the fMRI data analysis can be found in the Supplemental Experimental Procedures.

Visual Acuity Measurement

In addition to monocular tests with the classical letter acuity chart (see Table S1), participants' vision was tested binocularly (i.e., the conditions of viewing in everyday life and in the scanner). They wore their normal glasses or contact lenses, which in every case corrected at least one eye for the testing distance. We used computerized tests evaluating visual acuity, contrast sensitivity, and vernier discrimination [54]. These tests were done on the same day, or the day after, the MRI recording (see the Supplemental Experimental Procedures). The obtained scores were regressed with the individual contrast images (motion + voice) to identify any brain region where response to sounds was correlated to the visual deficits in the cataract-reversal group (see Figures S1.9A–9D).

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, one figure, and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.07.036.

AUTHOR CONTRIBUTIONS

O.C., G.D., A.d.H., F.L., T.L.L., and D.M. designed the experiment and wrote the paper. O.C., G.D., and A.d.H. conducted the experiments. O.C. carried out the analyses.

ACKNOWLEDGMENTS

The authors thank Sally Stafford for her invaluable help in recruiting the participants. This research was supported in part by the Quebec Bio-Imaging Network "pilot project" grant (F.L. and O.C.), the Canadian Institutes of Health Research (F.L., D.M., and T.L.L.), the Sainte-Justine Hospital Fundation (O.C.), the Belgian National Funds for Scientific Research (G.D. and A.d.H.), and the "MADVIS" European Research Council starting grant (O.C.; ERC-StG 337573).

Received: May 28, 2015
Revised: July 11, 2015
Accepted: July 14, 2015
Published: August 20, 2015

REFERENCES

1. Blakemore, C., and Cooper, G.F. (1970). Development of the brain depends on the visual environment. Nature *228*, 477–478.
2. Wiesel, T.N., and Hubel, D.H. (1965). Extent of recovery from the effects of visual deprivation in kittens. J. Neurophysiol. *28*, 1060–1072.
3. Riesen, A. (1950). Arrested vision. Sci. Am. *183*, 16–19.
4. Lewis, T.L., and Maurer, D. (2005). Multiple sensitive periods in human visual development: evidence from visually deprived children. Dev. Psychobiol. *46*, 163–183.
5. Röder, B., Ley, P., Shenoy, B.H., Kekunnaya, R., and Bottari, D. (2013). Sensitive periods for the functional specialization of the neural system for human face processing. Proc. Natl. Acad. Sci. USA *110*, 16760–16765.
6. Grady, C.L., Mondloch, C.J., Lewis, T.L., and Maurer, D. (2014). Early visual deprivation from congenital cataracts disrupts activity and functional connectivity in the face network. Neuropsychologia *57*, 122–139.
7. McCulloch, D.L., and Skarf, B. (1994). Pattern reversal visual evoked potentials following early treatment of unilateral, congenital cataract. Arch. Ophthalmol. *112*, 510–518.
8. Bavelier, D., and Neville, H.J. (2002). Cross-modal plasticity: where and how? Nat. Rev. Neurosci. *3*, 443–452.
9. Pascual-Leone, A., Amedi, A., Fregni, F., and Merabet, L.B. (2005). The plastic human brain cortex. Annu. Rev. Neurosci. *28*, 377–401.
10. Stephan, K.E., Penny, W.D., Daunizeau, J., Moran, R.J., and Friston, K.J. (2009). Bayesian model selection for group studies. Neuroimage *46*, 1004–1017.
11. Tootell, R.B., Mendola, J.D., Hadjikhani, N.K., Ledden, P.J., Liu, A.K., Reppas, J.B., Sereno, M.I., and Dale, A.M. (1997). Functional analysis of V3A and related areas in human visual cortex. J. Neurosci. *17*, 7060–7078.
12. Tsao, D.Y., Vanduffel, W., Sasaki, Y., Fize, D., Knutsen, T.A., Mandeville, J.B., Wald, L.L., Dale, A.M., Rosen, B.R., Van Essen, D.C., et al. (2003). Stereopsis activates V3A and caudal intraparietal areas in macaques and humans. Neuron *39*, 555–568.
13. Banks, M.S., Aslin, R.N., and Letson, R.D. (1975). Sensitive period for the development of human binocular vision. Science *190*, 675–677.
14. Fawcett, S.L., Wang, Y.Z., and Birch, E.E. (2005). The critical period for susceptibility of human stereopsis. Invest. Ophthalmol. Vis. Sci. *46*, 521–525.

15. Ellemberg, D., Lewis, T.L., Maurer, D., Brar, S., and Brent, H.P. (2002). Better perception of global motion after monocular than after binocular deprivation. Vision Res. *42*, 169–179.
16. Tytla, M.E., Lewis, T.L., Maurer, D., and Brent, H.P. (1993). Stereopsis after congenital cataract. Invest. Ophthalmol. Vis. Sci. *34*, 1767–1773.
17. Collignon, O., Dormal, G., Albouy, G., Vandewalle, G., Voss, P., Phillips, C., and Lepore, F. (2013). Impact of blindness onset on the functional organization and the connectivity of the occipital cortex. Brain *136*, 2769–2783.
18. Flechsig, E., Shmerling, D., Hegyi, I., Raeber, A.J., Fischer, M., Cozzio, A., von Mering, C., Aguzzi, A., and Weissmann, C. (2000). Prion protein devoid of the octapeptide repeat region restores susceptibility to scrapie in PrP knockout mice. Neuron *27*, 399–408.
19. Dormal, G., and Collignon, O. (2011). Functional selectivity in sensory-deprived cortices. J. Neurophysiol. *105*, 2627–2630.
20. Collignon, O., Vandewalle, G., Voss, P., Albouy, G., Charbonneau, G., Lassonde, M., and Lepore, F. (2011). Functional specialization for auditory-spatial processing in the occipital cortex of congenitally blind humans. Proc. Natl. Acad. Sci. USA *108*, 4435–4440.
21. Bremmer, F., Schlack, A., Shah, N.J., Zafiris, O., Kubischik, M., Hoffmann, K., Zilles, K., and Fink, G.R. (2001). Polymodal motion processing in posterior parietal and premotor cortex: a human fMRI study strongly implies equivalencies between humans and monkeys. Neuron *29*, 287–296.
22. Poirier, C., Collignon, O., Devolder, A.G., Renier, L., Vanlierde, A., Tranduy, D., and Scheiber, C. (2005). Specific activation of the V5 brain area by auditory motion processing: an fMRI study. Brain Res. Cogn. Brain Res. *25*, 650–658.
23. Poirier, C., Collignon, O., Scheiber, C., Renier, L., Vanlierde, A., Tranduy, D., Veraart, C., and De Volder, A.G. (2006). Auditory motion perception activates visual motion areas in early blind subjects. Neuroimage *31*, 279–285.
24. Belin, P., Zatorre, R.J., Lafaille, P., Ahad, P., and Pike, B. (2000). Voice-selective areas in human auditory cortex. Nature *403*, 309–312.
25. Ricciardi, E., and Pietrini, P. (2011). New light from the dark: what blindness can teach us about brain function. Curr. Opin. Neurol. *24*, 357–363.
26. Reich, L., Maidenbaum, S., and Amedi, A. (2012). The brain as a flexible task machine: implications for visual rehabilitation using noninvasive vs. invasive approaches. Curr. Opin. Neurol. *25*, 86–95.
27. Collignon, O., Dormal, G., and Lepore, F. (2012). Building the brain in the dark: functional and specific crossmodal reorganization in the occipital cortex of blind individuals. In Plasticity in Sensory Systems, M. Jenkin, J. Steeves, and L. Harris, eds. (Cambridge University Press).
28. Carlson, S., Pertovaara, A., and Tanila, H. (1987). Late effects of early binocular visual deprivation on the function of Brodmann's area 7 of monkeys (Macaca arctoides). Brain Res. *430*, 101–111.
29. Saenz, M., Lewis, L.B., Huth, A.G., Fine, I., and Koch, C. (2008). Visual Motion Area MT+/V5 Responds to Auditory Motion in Human Sight-Recovery Subjects. J. Neurosci. *28*, 5141–5148.
30. Dormal, G., Lepore, F., Harissi-Dagher, M., Albouy, G., Bertone, A., Rossion, B., and Collignon, O. (2015). Tracking the evolution of cross-modal plasticity and visual functions before and after sight restoration. J. Neurophysiol. *113*, 1727–1742.
31. Klinge, C., Eippert, F., Röder, B., and Büchel, C. (2010). Corticocortical connections mediate primary visual cortex responses to auditory stimulation in the blind. J. Neurosci. *30*, 12798–12805.
32. Maffei, A., and Turrigiano, G. (2008). The age of plasticity: developmental regulation of synaptic plasticity in neocortical microcircuits. Prog. Brain Res. *169*, 211–223.
33. Huttenlocher, P.R., and de Courten, C. (1987). The development of synapses in striate cortex of man. Hum. Neurobiol. *6*, 1–9.
34. Dehay, C., Kennedy, H., and Bullier, J. (1988). Characterization of transient cortical projections from auditory, somatosensory, and motor cortices to visual areas 17, 18, and 19 in the kitten. J. Comp. Neurol. *272*, 68–89.
35. Innocenti, G.M., and Clarke, S. (1984). Bilateral transitory projection to visual areas from auditory cortex in kittens. Brain Res. *316*, 143–148.
36. Kennedy, H., Bullier, J., and Dehay, C. (1989). Transient projection from the superior temporal sulcus to area 17 in the newborn macaque monkey. Proc. Natl. Acad. Sci. USA *86*, 8093–8097.
37. Falchier, A., Clavagnier, S., Barone, P., and Kennedy, H. (2002). Anatomical evidence of multimodal integration in primate striate cortex. J. Neurosci. *22*, 5749–5759.
38. Rockland, K.S., and Ojima, H. (2003). Multisensory convergence in calcarine visual areas in macaque monkey. Int. J. Psychophysiol. *50*, 19–26.
39. Berman, N.E. (1991). Alterations of visual cortical connections in cats following early removal of retinal input. Brain Res. Dev. Brain Res. *63*, 163–180.
40. Yaka, R., Yinon, U., and Wollberg, Z. (1999). Auditory activation of cortical visual areas in cats after early visual deprivation. Eur. J. Neurosci. *11*, 1301–1312.
41. Karlen, S.J., Kahn, D.M., and Krubitzer, L. (2006). Early blindness results in abnormal corticocortical and thalamocortical connections. Neuroscience *142*, 843–858.
42. Collignon, O., Voss, P., Lassonde, M., and Lepore, F. (2009). Cross-modal plasticity for the spatial processing of sounds in visually deprived subjects. Exp. Brain Res. *192*, 343–358.
43. Guerreiro, M.J., Putzar, L., and Röder, B. (2015). The effect of early visual deprivation on the neural bases of multisensory processing. Brain *138*, 1499–1504.
44. Iurilli, G., Ghezzi, D., Olcese, U., Lassi, G., Nazzaro, C., Tonini, R., Tucci, V., Benfenati, F., and Medini, P. (2012). Sound-driven synaptic inhibition in primary visual cortex. Neuron *73*, 814–828.
45. Putzar, L., Goerendt, I., Lange, K., Rösler, F., and Röder, B. (2007). Early visual deprivation impairs multisensory interactions in humans. Nat. Neurosci. *10*, 1243–1245.
46. Carriere, B.N., Royal, D.W., Perrault, T.J., Morrison, S.P., Vaughan, J.W., Stein, B.E., and Wallace, M.T. (2007). Visual deprivation alters the development of cortical multisensory integration. J. Neurophysiol. *98*, 2858–2867.
47. Collignon, O., Lassonde, M., Lepore, F., Bastien, D., and Veraart, C. (2007). Functional cerebral reorganization for auditory spatial processing and auditory substitution of vision in early blind subjects. Cereb. Cortex *17*, 457–465.
48. Collignon, O., Davare, M., Olivier, E., and De Volder, A.G. (2009). Reorganisation of the right occipito-parietal stream for auditory spatial processing in early blind humans. A transcranial magnetic stimulation study. Brain Topogr. *21*, 232–240.
49. Lee, D.S., Lee, J.S., Oh, S.H., Kim, S.K., Kim, J.W., Chung, J.K., Lee, M.C., and Kim, C.S. (2001). Cross-modal plasticity and cochlear implants. Nature *409*, 149–150.
50. Doucet, M.E., Bergeron, F., Lassonde, M., Ferron, P., and Lepore, F. (2006). Cross-modal reorganization and speech perception in cochlear implant users. Brain *129*, 3376–3383.
51. Strelnikov, K., Rouger, J., Demonet, J.F., Lagleyre, S., Fraysse, B., Deguine, O., and Barone, P. (2013). Visual activity predicts auditory recovery from deafness after adult cochlear implantation. Brain *136*, 3682–3695.
52. Collignon, O., Champoux, F., Voss, P., and Lepore, F. (2011). Sensory rehabilitation in the plastic brain. Prog. Brain Res. *191*, 211–231.
53. Lewis, T.L., Maurer, D., and Brent, H.P. (1995). Development of grating acuity in children treated for unilateral or bilateral congenital cataract. Invest. Ophthalmol. Vis. Sci. *36*, 2080–2095.
54. Bach, M. (1996). The Freiburg Visual Acuity test–automatic measurement of visual acuity. Optom. Vis. Sci. *73*, 49–53.