Current Biology

Report

# A Brief Period of Postnatal Visual Deprivation Alters the Balance between Auditory and Visual Attention

## Highlights

- We studied adults treated for congenital bilateral cataracts in infancy
- Short and early visual deprivation triggers enhanced auditory processing
- Cataract-reversal patients have atypical attentional balance between audition and vision
- Short postnatal visual deprivation preserves simple multisensory integration

## Authors

Adélaïde de Heering, Giulia Dormal, Maxime Pelland, Terri Lewis, Daphne Maurer, Olivier Collignon

## Correspondence

olivier.collignon@uclouvain.be

## In Brief

de Heering et al. propose that the absence of visual input during a brief period early in life alters the competitive balance between the visual and auditory systems and triggers enhanced sensory and attentional salience for simple auditory stimuli, while preserving normal multisensory integration of simple targets.

de Heering et al., 2016, Current Biology *26*, 1–5
November 21, 2016
http://dx.doi.org/10.1016/j.cub.2016.10.014

CellPress

Please cite this article in press as: de Heering et al., A Brief Period of Postnatal Visual Deprivation Alters the Balance between Auditory and Visual Attention, Current Biology (2016), http://dx.doi.org/10.1016/j.cub.2016.10.014

Current Biology
Report
CellPress

# A Brief Period of Postnatal Visual Deprivation Alters the Balance between Auditory and Visual Attention

**Adélaïde de Heering,[1] Giulia Dormal,[2,3,6] Maxime Pelland,[3] Terri Lewis,[4,5] Daphne Maurer,[4,5] and Olivier Collignon[6,7,8,*]**
[1]UNESCOG, Center for Cognition & Neurosciences, Université Libre de Bruxelles, Avenue F. Roosevelt, 50 CP 191, 1050 Bruxelles, Belgium
[2]Biological Psychology and Neuropsychology, University of Hamburg, Von-Melle-Park 11, 20146 Hamburg, Germany
[3]Centre de Recherche en Neuropsychologie et Cognition (CERNEC), Université de Montréal, Marie-Victorin Building, Station Centre-ville, Montréal, QC H3C 3J7, Canada
[4]Department of Psychology, Neuroscience & Behaviour, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4K1, Canada
[5]The Hospital for Sick Children, Toronto, ON M5G 1X8, Canada
[6]Institute of Research in Psychology (IPSY) and in Neuroscience (IoNS), University of Louvain, Place du Cardinal Mercier 10, 1348 Louvain-la-Neuve, Belgium
[7]Centro Interdipartimentale Mente/Cervello (CIMeC), Università di Trento, Via delle Regole 101, 38123 Mattarello, Italy
[8]Lead Contact
*Correspondence: olivier.collignon@uclouvain.be
http://dx.doi.org/10.1016/j.cub.2016.10.014

## SUMMARY

**Is a short and transient period of visual deprivation early in life sufficient to induce lifelong changes in how we attend to, and integrate, simple visual and auditory information [1, 2]? This question is of crucial importance given the recent demonstration in both animals and humans that a period of blindness early in life permanently affects the brain networks dedicated to visual, auditory, and multisensory processing [1–16]. To address this issue, we compared a group of adults who had been treated for congenital bilateral cataracts during early infancy with a group of normally sighted controls on a task requiring simple detection of lateralized visual and auditory targets, presented alone or in combination. Redundancy gains obtained from the audiovisual conditions were similar between groups and surpassed the reaction time distribution predicted by Miller's race model. However, in comparison to controls, cataract-reversal patients were faster at processing simple auditory targets and showed differences in how they shifted attention across modalities. Specifically, they were faster at switching attention from visual to auditory inputs than in the reverse situation, while an opposite pattern was observed for controls. Overall, these results reveal that the absence of visual input during the first months of life does not prevent the development of audiovisual integration but enhances the salience of simple auditory inputs, leading to a different crossmodal distribution of attentional resources between auditory and visual stimuli.**

## RESULTS AND DISCUSSION

We examined whether a short period of visual deprivation during the early sensitive period of brain development leads to enduring alterations in the perceptual integration and the attentional balance of auditory and visual information. To this end, we contrasted the reaction times of a group of 13 cataract-reversal patients to those of 13 gender- and age-matched typically sighted controls. The task was to press a response key with the preferred index finger when participants detected simple auditory (beeps) and visual (flashes) targets presented alone or in combination (for more details, see the Supplemental Experimental Procedures). All stimuli were lateralized to promote the contribution of the superior colliculus, which is known to be involved in multisensory integration [3] and altered in cases of early visual deprivation [4, 6] (also see the Supplemental Experimental Procedures). The data of one patient (NA) were excluded from all the analyses because she was sleepy during testing and had accuracy deviating by more than 2.5 SDs from the group mean in all experimental conditions. Thus, the final sample of patients consisted of 12 individuals (seven male; mean age = 23 years, range = 17–32 years; for patient inclusion criteria, see the Supplemental Experimental Procedures) born with dense bilateral cataracts that prevented any patterned visual input until they were removed surgically and the eyes fitted with contact lenses. Patients' duration of deprivation, from birth until they were first fitted with contact lenses, ranged from 9 to 238 days (mean deprivation period = 121 days) and their visual (logMAR) acuity ranged from 0.1 to 0.7 (mean = 0.3).

Early visual deprivation negatively impacts the development of many, but not all, visual capabilities. Even when treatment occurs during infancy, there are later deficits in sensitivity to high spatial frequencies [17], global form (in Glass patterns [18]), global motion [19], and the extraction of configural/holistic facial information [20, 21], a skill related to expert face processing [11]. Nevertheless such deprivation does not prevent the later development of sensitivity to low spatial frequencies [17], biological motion [19], intact versus scrambled face detection [22], and of the processing of the shape of internal facial features and of the facial external contour [20]. In contrast, the impact of early visual deprivation on auditory processing has been less systematically investigated. In one of the few studies to date, patients' auditory processing was described as not differing from that of controls at the behavioral level [23].

Multisensory integration develops over a protracted period of time [24–27]. Depending on the task requirement [2], it has often been described as affected by an early and transient period of visual deprivation [1, 12, 13]. Animal studies also have shown that temporarily eliminating visual experience early in life has a profound effect on the neural bases of multisensory integration, abolishing it in subcortical neurons (superior colliculus [3, 4, 6]) and changing enhancement to depression in cortical neurons [5].

In the present study, we used an audiovisual paradigm that allowed us to simultaneously assess differences between cataract-reversal patients and controls in their ability to detect and integrate simple visual and auditory stimuli and to balance their attention between these stimuli. We chose stimuli easily detectable by both groups whose data could therefore be subjected to three different types of analyses: (1) reaction times and redundancy gains, (2) race model analyses, and (3) modality switch cost analyses (see the Supplemental Experimental Procedures for details).

## Reaction Times and Redundancy Gains

Both groups responded faster to bimodal signals (BI-congruent and BI-incongruent) than to a unimodal signal (auditory or visual) ($F[3,69] = 104.588$, $p < 0.0001$). An interaction between conditions and groups ($F[3,69] = 12.48$, $p < 0.0001$) revealed that patients processed auditory inputs faster than visual inputs ($t[11] = -5.336$, $p < 0.0001$) and that they did so faster than controls ($t[23] = -2.455$, $p = 0.022$; Figure 1A). Conversely, patients were not faster than controls at detecting visual targets presented alone ($p$ values $> 0.05$). Patients' auditory reaction times were not correlated with the duration of their deprivation period (one-tailed Pearson correlation: $p > 0.05$) or their visual acuity on the day of testing (one-tailed Spearman correlation: $p > 0.05$; the "visual acuity" variable violated the Shapiro test of normality [$p < 0.05$]).

To evaluate whether patients' faster responses to auditory inputs could have arisen from a shift of criterion of the type caused by differences in motivation or arousal level between the groups, we compared their reaction time distributions using ex-Gaussian analyses (with a special emphasis on the tau component; see the Supplemental Experimental Procedures). These analyses did not reveal any significant difference between the patient and the control group, which does not support the idea that criterion shifts explain the patients' atypical pattern of results.

Participants' redundancy gains were calculated in order to explore the advantage of the bimodal conditions over the best unimodal condition [28–31]. Both groups were faster in the multisensory conditions relative to the best (fastest) unisensory condition, as shown by the finding that the redundancy gain was significantly different from 0 in both groups and for both congruent and incongruent trials (one-sample t tests against 0: $p$ values $< 0.05$; Figure 1B). An ANOVA on these scores with congruency (congruent, incongruent) as the within-subject factor and the group (patient, control) as the between-subject factor indicated only an overall advantage of congruent over incongruent trials ($F[1,23] = 4.959$, $p = 0.036$). No other effect or interaction involving the group factor was significant ($p > 0.20$) (for Bayesian statistics, see the Supplemental Experimental Procedures). As with reaction times, patients' redundancy gains were not correlated with the duration of their deprivation period (one-tailed Pearson correlation: $p$ values $> 0.05$) or their visual acuity on the day of testing (one-tailed Spearman correlation: $p$ values $> 0.05$).

## Race Model

To further explore multisensory integration in the patient group, we tested for violation of Miller's race model prediction [32]. This procedure is widely used to better assess reaction time facilitation observed with multisensory stimuli [33]. It relies on the comparison of participants' reaction times in multisensory conditions to the minimum sum of their unisensory response distributions. This model suggests that if sensory information is processed through independent channels, the fastest unisensory stimulus determines, as in a race, the observable multisensory reaction times. When the prediction of the race model is violated and the activation of two stimuli in combination induces faster responses overall, the speed-up in reaction times is associated with some form of multisensory integration (although whether it signals the merging of the signals into a single signal before the decision is debated [34]).

For these analyses, participants' reaction times from each unisensory condition (the bound in the model) were first subtracted from their reaction times in the redundant (bimodal) conditions. Both groups violated the race model over the fastest percentiles, up to 45%–55% (for more details, see the Supplemental Experimental Procedures). Second, participants' differential reaction times were averaged over the first five percentiles of the reaction time distribution (5%–45%), given that, as in previous studies [28, 35, 36], only this part of the distribution violated the race model (Figure 1C). Furthermore, an ANOVA on the average extent of violation with congruency (congruent, incongruent) as a within-subject variable and the group (patient, control) as a between-subject variable indicated no main effect of group nor any interaction involving the group factor ($F[1,23] = 1.415$, $p = 0.246$; Figure 1D) (for Bayesian statistics, see the Supplemental Experimental Procedures). The average extent of violation in this percentile range did not correlate with the patients' duration of deprivation (one-tailed Pearson correlations: $p$ values $> 0.05$) or with their visual acuity at the time of testing (one-tailed Spearman correlations: $p$ values $> 0.05$).

## Modality Switch Cost

In our paradigm, auditory, visual, and audiovisual conditions were presented in a stochastic fashion. This allowed us to investigate for the first time with a population suffering from early visual deprivation how trial history impacted their reaction times by analyzing the effect of the preceding trial on the next one [37, 38]. Modality switch cost analyses were taken as a proxy of sensory attentional capture because they partly highlight why, at a perceptual level, participants respond faster to bimodal signals than to unimodal signals [28, 35–39]. Specifically, it has been shown that switching attention between modalities increases the reaction times to unimodal stimuli, whereas the reaction times to bimodal stimuli are unaffected. In other words,

Please cite this article in press as: de Heering et al., A Brief Period of Postnatal Visual Deprivation Alters the Balance between Auditory and Visual Attention, Current Biology (2016), http://dx.doi.org/10.1016/j.cub.2016.10.014

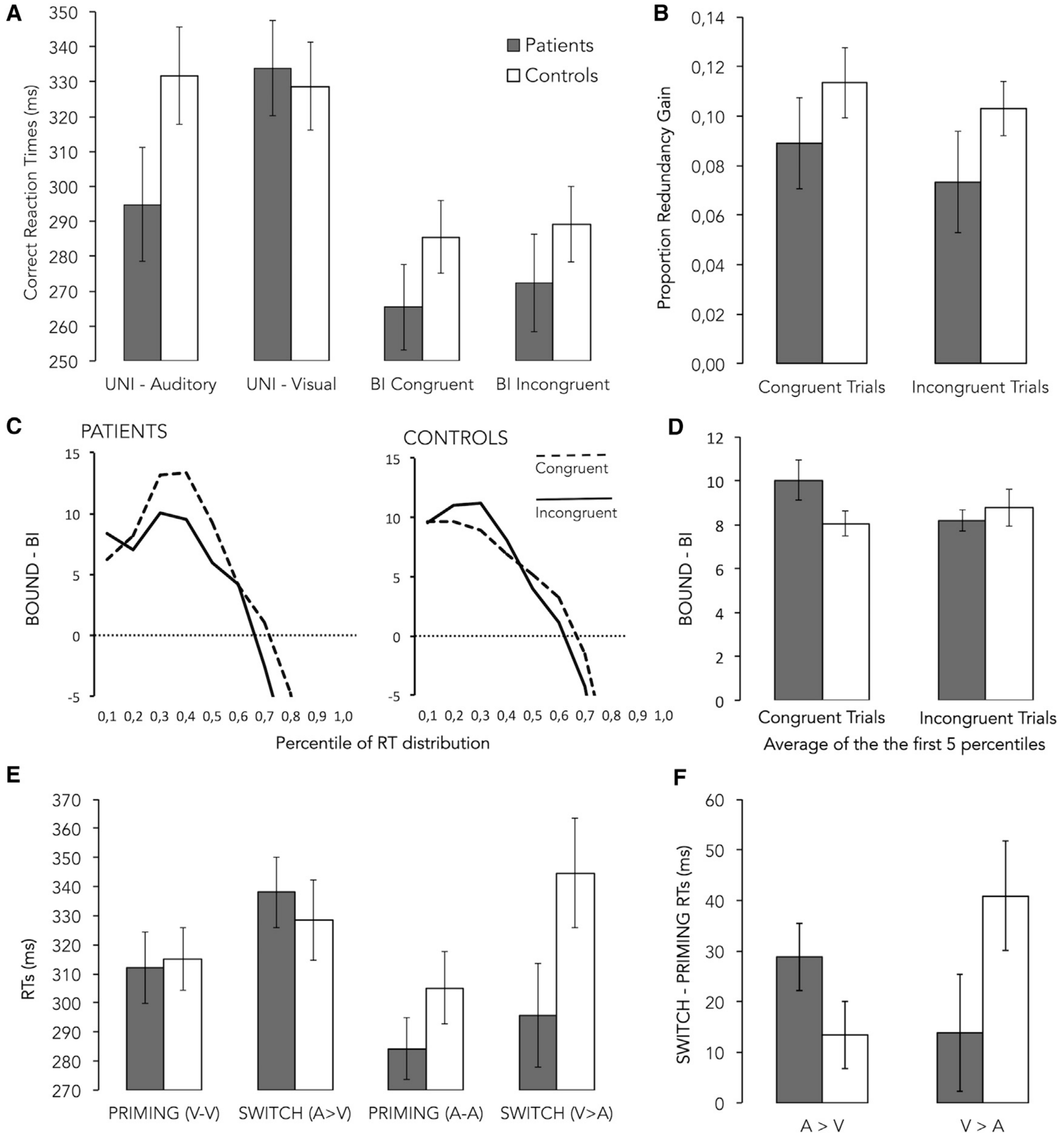

**Figure 1. Mean Data of the Patient Group and the Control Group When They Processed Simple Visual and Auditory Stimuli Presented Alone or in Combination**

(A) Correct reaction times (ms) across unimodal (auditory [A], visual [V]) and bimodal conditions (BI-congruent, BI-incongruent). Patients (black bars) were faster than controls (white bars) in detecting simple auditory information. Error bars indicate SEM.

(B) Redundancy gains ([best modality reaction times − redundant reaction times]/best modality reaction times) expressed as proportions, for congruent and incongruent trials. Patients (black bars) and controls (white bars) did not differ significantly on these scores, suggesting no multisensory integration deficit in the patient group. Error bars indicate SEM.

(C) Participants' reaction time distributions for audiovisual stimuli compared to the reaction times predicted by the race model presented for every ten percentiles of their reaction time distribution (on the x axis) for congruent (dashed lines) and incongruent (solid lines) trials. Left panel shows curves for patients and right panel shows curves for controls. These graphs depict the difference in milliseconds (on the y axis) between the model prediction computed from the reaction times of each unisensory counterpart (the model's bound) and participants' reaction times obtained in the redundant conditions (BI). Positive and negative values refer to reaction times that are faster or slower than the race model prediction, respectively. Both groups' reaction times violated the race model at the fastest percentiles.

(D) The side graph shows participants' averaged responses over the first five percentiles for congruent (left) and incongruent (right) trials. Both groups' violation of the race model was of equal magnitude for both types of trials. Patients, black bars; controls, white bars.

(E) Modality switch cost effects (ms) were calculated according to whether the previous stimulus was of the same (e.g., two successive visual stimuli; priming condition) or of a different modality (e.g., an auditory stimulus preceded by a visual stimulus; switch condition). Patients, black bars; controls, white bars.

(F) Modality switch cost indexes calculated as the difference between participants' reaction times in the conditions necessitating a switch of attention (switch) from the conditions that did not necessitate such a switch (priming). Patients (black bars) were faster to switch from visual to auditory detection compared to controls (white bars). Error bars indicate SEM. See also Table S1.

it is not the integrated percept that is affected by a switch of attention but rather its single components [37].

We speculated that patients' advantage at processing simple auditory stimuli could have impacted the attentional balance that they distribute to the auditory and visual modalities (see [39] for similar reasoning in dyslexics). As can be seen in Figure 1E, responses were overall faster when the same stimulus was presented on consecutive trials (i.e., priming) than when the stimuli on consecutive trials belonged to different modalities (e.g., when the participant was presented with a visual stimulus directly after an auditory stimulus), so that attention had to shift from one modality to another. The ease with which patients came back to their preferred auditory modality was emphasized when their modality switch cost effects (expressed in milliseconds, Figure 1E) and indexes (i.e., switch – priming, Figure 1F) were compared to those of controls.

An ANOVA on participants' indexes with the modality of the stimulus (visual, auditory) as the within-subject factor and the group (patient, control) as the between subject factor indicated no main effect of condition (F[1,22] = 0.402, p = 0.532) and no main effect of group (F[1,22] = 0.327, p = 0.573) but a significant interaction between the modality and the group (F[1,22] = 4.990, p = 0.036). Follow-up analyses revealed that controls took significantly more time to switch from the visual modality to the auditory modality than vice versa (V > A versus A > V; t[12] = −2.209, p = 0.047), while it was not the case for patients (t[10] = 1.038, p = 0.324; Figure 1F). Actually, when considering only the switching conditions, patients switched their attention faster from the visual to the auditory modality (V-A) than in the reverse situation (A-V) (t[10] = 3.85, p = 0.003; Figures 1E and 1F), while no difference was observed for the control group under the same testing conditions (t[12] = −1.644, p = 0.126). Patients' indexes in the V-A condition did not correlate with their duration of deprivation (one-tailed Pearson correlations: p values > 0.05) or visual acuity (one-tailed Spearman correlations: p values > 0.05). Finally, none of the ex-Gaussian analyses involving the *tau* component and performed on these data for similar reasons as those described above revealed any significant difference between the patient and the control group, which suggests that criterion shifts cannot explain patients' differential balance between auditory and visual attention (see the Supplemental Experimental Procedures).

## Conclusions

Together, these findings suggest that cataract-reversal patients give enhanced salience to auditory stimuli, as measured by faster reaction times on auditory trials and faster switches from vision to audition when compared to controls. This enhanced speed at detecting auditory targets is reminiscent of the one found after early-acquired and permanent blindness in humans [40]. Our results also suggest that the absence of visual inputs for several months after birth induces a change in the competitive balance between the visual and the auditory modality that impacts the detection of even simple targets. Similar findings have been observed for cochlear-implanted deaf patients whose superior multisensory integration capabilities compared to controls have been linked to their enhanced visual abilities, especially in noisy situations [41]. These findings also could be considered as the psychophysical counterpart of the observations that, like early blind individuals [42], cataract-reversal patients show enhanced reactivity in response to sounds in regions that typically process vision [7] and, unlike controls, lower visual cortical activity during audiovisual stimulation than during visual stimulation alone [8].

Despite the patients' unusual advantage for auditory detection, the redundancy gains and race model analyses indicate that they do not show any deficits for integrating simple auditory and visual targets (see Figures 1B–1D). The absence of multisensory integration deficits observed in this study confirms and extends the observation of a recent study by Putzar and colleagues [2] showing no alteration of multisensory integration in cataract-reversal individuals involved in a simple detection time task. As suggested by the authors, it is possible that patients' multisensory integration deficits are manifest only in specific tasks using more complex stimuli (e.g., face-voice integration [13]). It is also possible that these deficits occur only in tasks where patients' enhanced auditory salience of the type observed here interferes with an optimal integration [43]. In contrast, cataract-reversal patients appear to be able to overcome the altered multisensory integration seen in the brain in simpler contexts [1], perhaps through post-deprivation learning of the type documented in animals [44].

In conclusion, we propose that the absence of visual input for a brief period during early development induces an unbalanced competition between the visual and the auditory systems and triggers enhanced sensory and attentional salience for simple auditory targets, while preserving normal multisensory integration of simple targets.

## SUPPLEMENTAL INFORMATION

Supplemental Information includes one table and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2016.10.014.

## AUTHOR CONTRIBUTIONS

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

## ACKNOWLEDGMENTS

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

We would like to thank Sally Stafford for helping to collect the data. This research was supported by the Canadian Institutes of Health Research (D.M. and T.L.), the Sainte-Justine Hospital Foundation (O.C.), the Belgian National Funds for Scientific Research (A.d.H. and G.D.), and the European Research Council (O.C.; starting grant ERC-StG 337573; MADVIS). O.C. is a research associate at the Belgian National Funds for Scientific Research.

Received: July 6, 2016
Revised: September 14, 2016
Accepted: October 10, 2016
Published: November 10, 2016

## REFERENCES

1. 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.

Please cite this article in press as: de Heering et al., A Brief Period of Postnatal Visual Deprivation Alters the Balance between Auditory and Visual Attention, Current Biology (2016), http://dx.doi.org/10.1016/j.cub.2016.10.014

2. Putzar, L., Gondan, M., and Röder, B. (2012). Basic multisensory functions can be acquired after congenital visual pattern deprivation in humans. Dev. Neuropsychol. *37*, 697–711.
3. Wallace, M.T., and Stein, B.E. (2007). Early experience determines how the senses will interact. J. Neurophysiol. *97*, 921–926.
4. Wallace, M.T., Perrault, T.J., Jr., Hairston, W.D., and Stein, B.E. (2004). Visual experience is necessary for the development of multisensory integration. J. Neurosci. *24*, 9580–9584.
5. 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.
6. Royal, D.W., Krueger, J., Fister, M.C., and Wallace, M.T. (2010). Adult plasticity of spatiotemporal receptive fields of multisensory superior colliculus neurons following early visual deprivation. Restor. Neurol. Neurosci. *28*, 259–270.
7. Collignon, O., Dormal, G., de Heering, A., Lepore, F., Lewis, T.L., and Maurer, D. (2015). Long-lasting crossmodal cortical reorganization triggered by brief postnatal visual deprivation. Curr. Biol. *25*, 2379–2383.
8. 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.
9. Fine, I., Smallman, H.S., Doyle, P., and MacLeod, D.I. (2002). Visual function before and after the removal of bilateral congenital cataracts in adulthood. Vision Res. *42*, 191–210.
10. Ostrovsky, Y., Andalman, A., and Sinha, P. (2006). Vision following extended congenital blindness. Psychol. Sci. *17*, 1009–1014.
11. Maurer, D., Lewis, T.L., and Mondloch, C.J. (2005). Missing sights: consequences for visual cognitive development. Trends Cogn. Sci. *9*, 144–151.
12. Putzar, L., Goerendt, I., Heed, T., Richard, G., Büchel, C., and Röder, B. (2010a). The neural basis of lip-reading capabilities is altered by early visual deprivation. Neuropsychologia *48*, 2158–2166.
13. Putzar, L., Hötting, K., and Röder, B. (2010b). Early visual deprivation affects the development of face recognition and of audio-visual speech perception. Restor. Neurol. Neurosci. *28*, 251–257.
14. Dormal, G., Lepore, F., Harissi-Dagher, M., Albouy, G., Bertone, A., Rossion, B., and Collignon, O. (2015). Tracking the evolution of crossmodal plasticity and visual functions before and after sight restoration. J. Neurophysiol. *113*, 1727–1742.
15. 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.
16. Huber, E., Webster, J.M., Brewer, A.A., MacLeod, D.I., Wandell, B.A., Boynton, G.M., Wade, A.R., and Fine, I. (2015). A lack of experience-dependent plasticity after more than a decade of recovered sight. Psychol. Sci. *26*, 393–401.
17. Ellemberg, D., Lewis, T.L., Maurer, D., Lui, C.H., and Brent, H.P. (1999). Spatial and temporal vision in patients treated for bilateral congenital cataracts. Vision Res. *39*, 3480–3489.
18. Lewis, T.L., Ellemberg, D., Maurer, D., Wilkinson, F., Wilson, H.R., Dirks, M., and Brent, H.P. (2002). Sensitivity to global form in glass patterns after early visual deprivation in humans. Vision Res. *42*, 939–948.
19. Hadad, B.S., Maurer, D., and Lewis, T.L. (2012). Sparing of sensitivity to biological motion but not of global motion after early visual deprivation. Dev. Sci. *15*, 474–481.
20. Le Grand, R., Mondloch, C.J., Maurer, D., and Brent, H.P. (2001). Neuroperception. Early visual experience and face processing. Nature *410*, 890.
21. Le Grand, R., Mondloch, C.J., Maurer, D., and Brent, H.P. (2004). Impairment in holistic face processing following early visual deprivation. Psychol. Sci. *15*, 762–768.
22. Mondloch, C.J., Le Grand, R., and Maurer, D. (2003). Early visual experience is necessary for the development of some—but not all—aspects of face processing. In The Development of Face Processing in Infancy and Early Childhood, O. Pascalis, and A. Slater, eds. (Nova Science Publishers), pp. 99–117.
23. Guerreiro, M.J., Putzar, L., and Röder, B. (2016). The effect of early visual deprivation on the neural bases of auditory processing. J. Neurosci. *36*, 1620–1630.
24. Lewkowicz, D.J., and Ghazanfar, A.A. (2009). The emergence of multisensory systems through perceptual narrowing. Trends Cogn. Sci. *13*, 470–478.
25. Murray, M.M., Foxe, J.J., Higgins, B.A., Javitt, D.C., and Schroeder, C.E. (2001). Visuo-spatial neural response interactions in early cortical processing during a simple reaction time task: a high-density electrical mapping study. Neuropsychologia *39*, 828–844.
26. Neil, P.A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D.J., and Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. Dev. Sci. *9*, 454–464.
27. Burr, D., and Gori, M. (2012). Multisensory integration develops late in humans. In The Neural Bases of Multisensory Processes, M.M. Murray, and M.T. Wallace, eds. (CRC Press/Taylor & Francis).
28. Girard, S., Collignon, O., and Lepore, F. (2011). Multisensory gain within and across hemispaces in simple and choice reaction time paradigms. Exp. Brain Res. *214*, 1–8.
29. Hershenson, M. (1962). Reaction time as a measure of intersensory facilitation. J. Exp. Psychol. *63*, 289–293.
30. Raab, D.H. (1962). Statistical facilitation of simple reaction times. Trans. N. Y. Acad. Sci. *24*, 574–590.
31. Todd, J.W. (1912). Reaction to Multiple Stimuli (Science Press).
32. Miller, J. (1982). Divided attention: evidence for coactivation with redundant signals. Cognit. Psychol. *14*, 247–279.
33. Colonius, H., and Diederich, A. (2006). The race model inequality: interpreting a geometric measure of the amount of violation. Psychol. Rev. *113*, 148–154.
34. Otto, T.U., and Mamassian, P. (2012). Noise and correlations in parallel perceptual decision making. Curr. Biol. *22*, 1391–1396.
35. Cappe, C., Thut, G., Romei, V., and Murray, M.M. (2009). Selective integration of auditory-visual looming cues by humans. Neuropsychologia *47*, 1045–1052.
36. Girard, S., Pelland, M., Lepore, F., and Collignon, O. (2013). Impact of the spatial congruence of redundant targets on within-modal and cross-modal integration. Exp. Brain Res. *224*, 275–285.
37. Gondan, M., Lange, K., Rösler, F., and Röder, B. (2004). The redundant target effect is affected by modality switch costs. Psychon. Bull. Rev. *11*, 307–313.
38. Spence, C., Nicholls, M.E.R., and Driver, J. (2001). The cost of expecting events in the wrong sensory modality. Percept. Psychophys. *63*, 330–336.
39. Harrar, V., Tammam, J., Pérez-Bellido, A., Pitt, A., Stein, J., and Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. Curr. Biol. *24*, 531–535.
40. Collignon, O., Charbonneau, G., Lassonde, M., and Lepore, F. (2009). Early visual deprivation alters multisensory processing in peripersonal space. Neuropsychologia *47*, 3236–3243.
41. Rouger, J., Fraysse, B., Deguine, O., and Barone, P. (2008). McGurk effects in cochlear-implanted deaf subjects. Brain Res. *1188*, 87–99.
42. 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.
43. Ernst, M.O., and Bülthoff, H.H. (2004). Merging the senses into a robust percept. Trends Cogn. Sci. *8*, 162–169.
44. Yu, L., Rowland, B.A., and Stein, B.E. (2010). Initiating the development of multisensory integration by manipulating sensory experience. J. Neurosci. *30*, 4904–4913.