

1 **Title: Dissociating instructive and reorganizing effects of experience on development of**  
2 **human visual cortices**

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13

14 **Abstract**

15

16 Comparisons across adults with different sensory histories (blind vs. sighted) have uncovered  
17 effects of experience on the development of human brain function. In people born blind  
18 visual cortices become responsive to non-visual tasks and show enhanced functional coupling  
19 with fronto-parietal executive systems at rest. Little is known about the developmental  
20 origins of experience-based plasticity in humans, since almost all research has been done with  
21 adults. Here we take a new approach by comparing resting state data across blind (n=30) and  
22 blindfolded sighted (n=50) adults to two large cohorts of sighted infants (dHCP, n=327,  
23 n=475). By comparing the infant “starting state” to adult outcomes, we dissociate the  
24 instructive role of vision from reorganization due to blindness. As previously reported, we  
25 find that in sighted adults, visual networks show stronger functional coupling with other  
26 sensory-motor networks (i.e., auditory, somatosensory) than with higher-cognitive prefrontal  
27 networks at rest. By contrast, visual cortices of adults born blind show the opposite pattern:  
28 stronger functional connectivity with higher-cognitive prefrontal networks. Remarkably, we  
29 find that the connectivity profile of secondary visual cortices in infants resembles that of  
30 blind more than sighted adults. Visual experience appears to ‘instruct’ coupling of visual  
31 cortex with other sensory-motor networks and de-couple from prefrontal systems. By contrast  
32 primary visual cortex (V1) shows a mixture of instructive effects of vision and reorganizing  
33 effects of blindness. Finally, lateralization of occipital connectivity appears to be driven by  
34 blindness-related reorganization, since infants resembles sighted adults. These results reveal  
35 instructive and reorganizing effect of experience on functional connectivity of human cortex.

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## 39 Introduction

40 Studies of visual development provide a model for understanding how early life experience  
41 shapes cortical function and behavior (Hensch, 2005; Hubel & Wiesel, 1970; Sadato et al.,  
42 1996). Research in visually deprived animals has identified both instructive and reorganizing  
43 effects of early life experience on cortical function (Espinosa & Stryker, 2012; Molnár et al.,  
44 2020; Reh et al., 2020). An example of reorganization comes from studies of ocular  
45 dominance columns in V1. Columnar organization is present from birth in most mammals but  
46 can be disrupted by imbalanced visual input from the two eyes early in life (Crair et al., 1998;  
47 Espinosa & Stryker, 2012; Horton & Hocking, 1996; Hubel & Wiesel, 1970; Katz &  
48 Crowley, 2002; Sengpiel & Kind, 2002). On the other hand, instructive effects of visual  
49 experience are observed in the case of direction selectivity in early visual cortices of ferrets.  
50 Direction selectivity is weak or absent at birth and requires visual motion experience to  
51 emerge (Li et al., 2006; Rochefort et al., 2011). In humans, visual cortex function and  
52 behavior differs in adulthood in cases of atypical early visual experience. However,  
53 instructive, and reorganizing effects on cortical function have not been dissociated, since until  
54 recently it has not been possible to measure cortical function in human infants.

55 Adults who had dense cataracts as infants show lower visual acuity, altered face and object  
56 recognition and multimodal integration (Badde et al., 2020; Guerreiro et al., 2015; Le Grand  
57 et al., 2001; Maurer et al., 2007; McKyton et al., 2015; Röder & Kekunnaya, 2021). Visual  
58 cortices of individuals born blind show enhanced ‘cross-modal’ responses during auditory  
59 and tactile tasks, such as Braille reading, spoken language comprehension, auditory spatial  
60 attention and auditory response selection (Bedny et al., 2011; Burton et al., 2012; Collignon  
61 et al., 2011; Kanjlia et al., 2021, 2021; Masuda et al., 2021; Sadato et al., 1996).

62 Differences in task-based responses across blind and sighted adults are accompanied by  
63 differences in spontaneous neural activity at rest i.e., differences in functional connectivity or  
64 resting state correlations (e.g. Liu et al., 2007). Resting state correlations have been widely  
65 used to identify functional networks across populations and are known to be constrained by  
66 anatomical connectivity and influenced by experience (Biswal et al., 1995; Lewis et al., 2009;  
67 Stevens et al., 2010).

68 Adults born blind show enhanced resting state correlations (relative to the sighted) between  
69 visual and prefrontal networks, especially those with analogous functions (Bedny et al., 2011;  
70 Burton et al., 2014; Liu et al., 2007; Striem-Amit et al., 2015; Watkins et al., 2012). For  
71 example, ‘visual’ areas that respond to spoken language and Braille in blind adults show  
72 enhanced functional connectivity with prefrontal language regions at rest, while those active  
73 during arithmetic tasks are more correlated with math-responsive prefrontal areas (PFC)  
74 (Abboud & Cohen, 2019; Bedny et al., 2011; Kanjlia et al., 2016, 2021). Interestingly, at rest,  
75 visual cortices of people born blind show *reduced* correlations with non-visual early sensory  
76 motor areas (i.e., auditory cortex A1, sensory-motor cortex S1/M1) (Bedny et al., 2011;  
77 Burton et al., 2014; Liu et al., 2007; Yu et al., 2008). This is even though during cross-modal  
78 tasks (e.g., auditory localization), visual areas of blind adults are more active and more  
79 correlated with these same non-visual sensory-motor areas (Collignon et al., 2011; Klinge et  
80 al., 2010).

81 In sum, in resting state data, visual cortices of sighted adults show stronger coupling with  
82 other non-visual sensory-motor networks, by contrast, in blind adults, this pattern is reversed  
83 and coupling is stronger with prefrontal cortices.

84 The developmental origins of cortical function differences across visual cortices of blind and  
85 sighted adults are not known. Since the vast majority of humans use vision, it is often  
86 assumed that population differences are driven by blindness related reorganization and the  
87 sighted adult pattern is the ‘default’ starting state. However, it is also possible that some of  
88 the population differences reflect lack of instructive effects of visual experience, i.e., infants  
89 start out as blind adults and vision gives rise to the sighted adult pattern. A potentially  
90 informative and previously unexplored approach that we take in the current study is to  
91 compare visual cortices of blind and sighted adults to that of sighted infants. To do so, we use  
92 resting state data, which provide a common measure across these diverse populations. We  
93 leverage previously documented functional connectivity differences between blind and  
94 sighted adults together with newly publicly available large resting state datasets from sighted  
95 infants (Developing Human Connectome Project (dHCP) dataset, second release:  $n=327$ ,  
96 third release:  $n=475$ ). With these data, we ask: Does blindness ‘reorganize’ resting state  
97 connectivity patterns that are common to sighted infants and sighted adults? Alternatively, do  
98 some of the differences between sighted and blind adults reflect an instructive role of vision  
99 in establishing connectivity patterns?

100 To our knowledge no prior study has directly compared resting state organization in infants to  
101 adult populations with different sensory histories. Previous resting state studies comparing  
102 sighted infants to sighted adults have largely reported similarities across groups, consistent  
103 with the idea that any differences between blind and sighted adults are due to blindness-  
104 driven reorganization (Doria et al., 2010; Fransson et al., 2009; Gao et al., 2009; W. C. Liu et  
105 al., 2008; Zhang et al., 2019). However, these prior studies have focused on connectivity  
106 *within* large scale functional networks (e.g., visual areas are more correlated with other visual  
107 areas than with somatosensory networks). Within network connectivity is arguably heavily  
108 constrained by large scale anatomical tracts and therefore unlikely to be influenced by  
109 experience. Differences between blind and sighted adults are observed in connectivity  
110 *between* the visual system and different non-visual functional networks i.e., which non-visual  
111 networks are most correlated with the visual system?

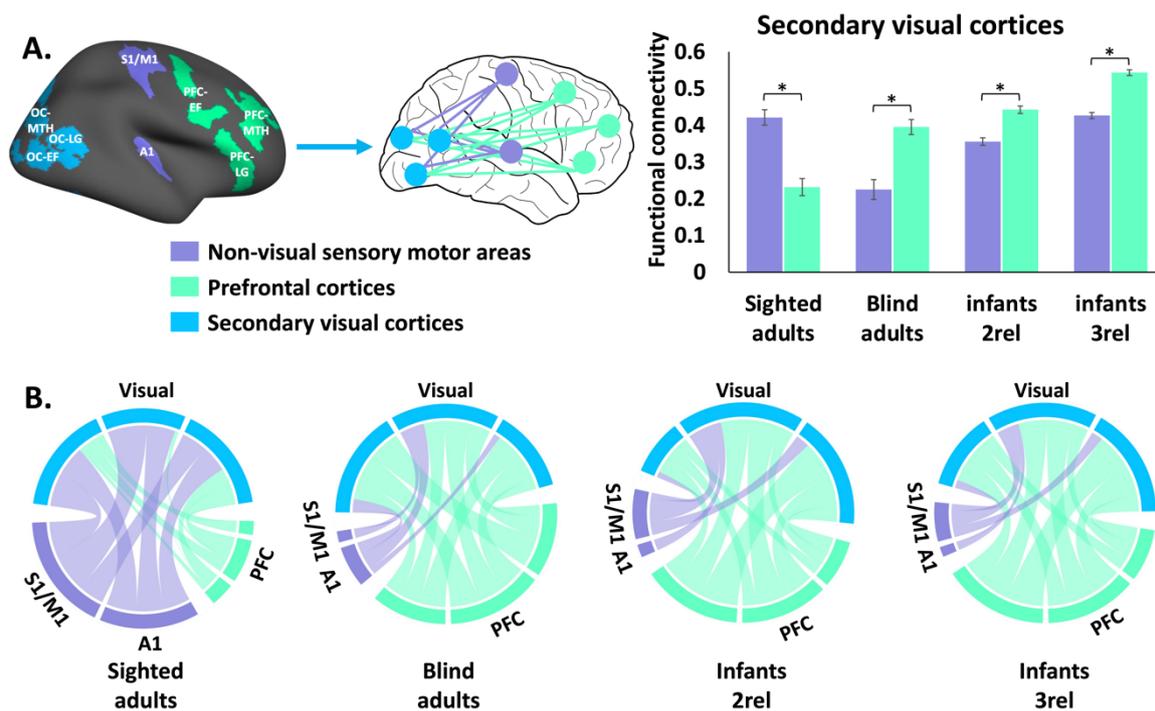
112 To preview the results, we find evidence for both instructive contribution of vision and  
113 reorganizing effects of blindness on visual system connectivity. Moreover, the effects of  
114 experience differ systematically across the visual hierarchy with more evidence for  
115 instructive effects of vision in higher-order visual areas than V1.

## 116 **Results & Discussion**

117 Secondary visual areas of sighted adults showed stronger functional connectivity with non-  
118 visual sensory areas (S1/M1 and primary auditory cortex, A1) than with prefrontal cortices  
119 (PFC). By contrast, in blind adults, visual cortices showed higher functional connectivity  
120 with PFC than with non-visual sensory areas (S1/M1 and A1) (group (sighted adults, blind  
121 adults) by ROI (PFC, non-visual sensory) interaction effect:  $F_{(1, 78)} = 148.819$ ,  $p < 0.001$ ;  
122 post-hoc Bonferroni-corrected paired  $t$ -test, sighted adults: non-visual sensory  $>$  PFC:  $t_{(49)} =$   
123  $9.722$ ,  $p < 0.001$ ; blind adults: non-visual sensory  $<$  PFC:  $t_{(29)} = 8.852$ ,  $p < 0.001$ ; Figure 1).

124 The connectivity profile of secondary visual cortex in sighted infants was more similar to that  
125 of blind than sighted adults, providing evidence for instructive effects of vision. In both  
126 samples of sighted infants, the secondary visual cortices showed higher connectivity to PFC  
127 than non-visual sensory areas (S1/M1 and A1) (non-visual sensory  $<$  PFC paired  $t$ -test in  
128 sighted infants, second release:  $t_{(326)} = 13.224$ ,  $p < 0.001$ ; third release:  $t_{(474)} = 20.144$ ,  $p <$

129 0.001) (Figure 1). The connectivity matrix of sighted infants was also more correlated with  
 130 that of blind than sighted adults, but strongly correlated with both adult groups (secondary  
 131 visual, PFC and non-visual sensory areas: infants correlated to blind adults: second release  $r$   
 132 = 0.663,  $p < 0.001$ ; third release  $r = 0.721$ ,  $p < 0.001$ ; to sighted adults: second release  $r =$   
 133 0.516,  $p < 0.001$ ; third release  $r = 0.524$ ,  $p < 0.001$ ; difference between correlations of infants  
 134 to blind vs. sighted adults: second release:  $z = 2.78$ ,  $p < 0.01$ ; third release:  $z = 3.77$ ,  $p <$   
 135 0.001; the comparison of correlation coefficients was done using cocor software package and  
 136 Pearson and Filon's  $z$  (Diedenhofen & Musch, 2015; Pearson & Filon, 1898). see  
 137 supplementary materials Figure S1 for the connectivity matrices). This result suggests that  
 138 visual experience enhances visual cortex connectivity at rest to non-visual sensory-motor  
 139 networks and dampens connectivity to higher-cognitive prefrontal networks.



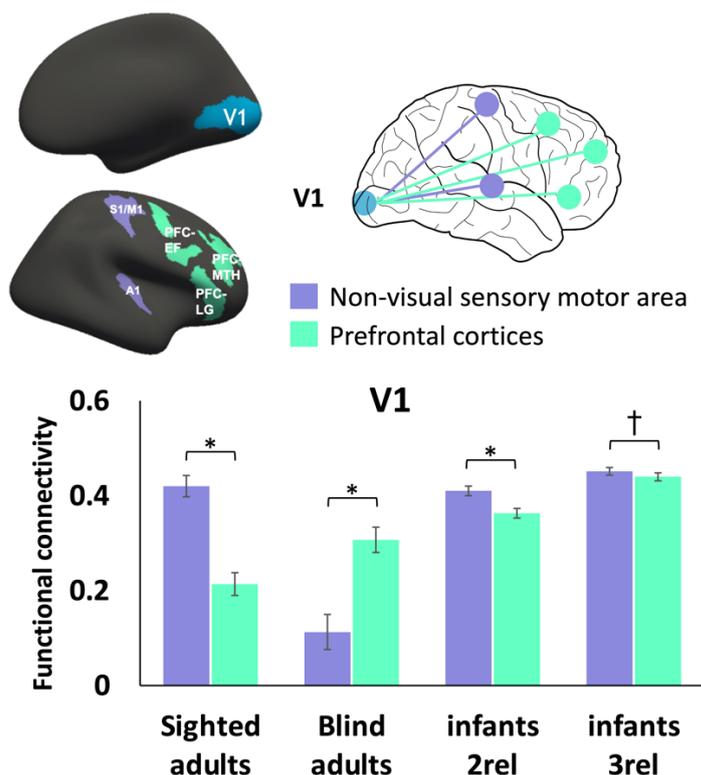
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141 **Figure 1** Functional connectivity of secondary visual cortices (blue) to non-visual sensory-motor networks  
 142 (purple) and prefrontal cortices (green) in sighted adults, blind adults and two cohorts of sighted infants  
 143 (2<sup>nd</sup> and 3<sup>rd</sup> release of dHCP). (A) Bar graph shows functional connectivity ( $r$ ) of secondary visual cortices  
 144 to non-visual sensory motor (purple) and PFC (green regions), averaged across occipital, PFC and sensory-  
 145 motor ROIs (A1 and S1/M1). Regions of interest displayed on the left. (B) Circle plots show connectivity  
 146 of secondary visual cortices to non-visual networks min-max normalized to [0,1] i.e., as a proportion. PFC:  
 147 prefrontal cortices; OC: occipital cortices; MTH: math-responsive region; LG: language-responsive region;  
 148 EF: executive function-responsive (response-conflict) region. Asterisks (\*) denote significant Bonferroni-  
 149 corrected pairwise comparisons ( $p < 0.05$ )

150 Next, we examined the functional connectivity of the primary visual cortex (V1) with non-  
 151 visual sensory areas (S1/M1 and primary auditory cortex, A1) and PFC. V1 showed the same  
 152 dissociation between sighted and blind adults as secondary visual areas: In sighted adults, V1  
 153 has stronger functional connectivity with non-visual sensory areas (S1/M1 and primary  
 154 auditory cortex, A1) than with PFC. By contrast, in blind adults, V1 shows stronger  
 155 connectivity with PFC than non-visual sensory areas (group (sighted adults, blind adults) by  
 156 ROI (PFC, non-visual sensory) interaction:  $F_{(1, 78)} = 125.775$ ,  $p < 0.001$ ; post-hoc Bonferroni-

157 corrected paired *t*-test, sighted adults non-visual sensory > PFC:  $t_{(49)} = 9.404, p < 0.001$ ;  
 158 blind adults non-visual sensory < PFC:  $t_{(29)} = 7.128, p < 0.001$ ; Figure 2).

159 For V1, the pattern for sighted infants fell between that of sighted and blind adults. The  
 160 connectivity matrix of the sighted infants (V1, PFC, and non-visual sensory) was equally  
 161 correlated with blind and sighted adults (infants correlated to blind adults: second release  $r =$   
 162  $0.613, p < 0.001$ ; third release  $r = 0.654, p < 0.001$ ; to sighted adults: second release  $r =$   
 163  $0.640, p < 0.001$ ; third release  $r = 0.594, p < 0.001$ ; correlation of infants with blind vs. with  
 164 Sighted: second release:  $z = 0.375, p = 0.707$ ; third release:  $z = 0.832, p = 0.406$ ; see  
 165 supplementary material Figure S1 for the connectivity matrices). V1 of infants showed  
 166 significantly stronger connectivity to non-visual sensory regions (A1 and S1/M1) than PFC in  
 167 the second release and marginally stronger connectivity in the third release (non-visual  
 168 sensory regions > PFC, paired *t*-test in sighted infants, second release:  $t_{(326)} = 6.814, p <$   
 169  $0.001$ ; third release:  $t_{(474)} = 1.95, p = 0.052$ ; Figure 2). The difference in connectivity strength  
 170 between PFC and non-visual sensory regions was weaker in sighted infants than in sighted or  
 171 blind adults (group (sighted adults, infants) by ROI (PFC, non-visual sensory) interaction  
 172 effect: second release:  $F_{(1, 375)} = 57.376, p < 0.001$ ; third release:  $F_{(1, 523)} = 92.21, p < 0.001$ ;  
 173 group (blind adults, infants) by ROI (PFC, non-visual sensory) interaction effect: second  
 174 release:  $F_{(1, 355)} = 81.632, p < 0.001$ ; third release:  $F_{(1, 503)} = 57.444, p < 0.001$ ). See  
 175 supplementary results for A1 and S1/M1 connectivity separately.



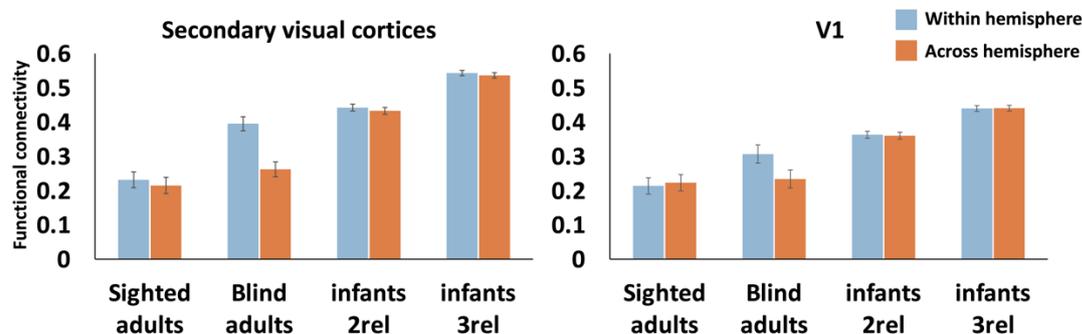
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177 **Figure 2** Functional connectivity of primary visual cortices (V1) to non-visual sensory-motor networks  
 178 (purple) and prefrontal cortices (green) in sighted adults, blind adults, and two cohorts of sighted infants  
 179 (2<sup>nd</sup> and 3<sup>rd</sup> release of dHCP). Regions of interest are shown in upper left. PFC: prefrontal cortices; MTH:  
 180 math-responsive region; LG: language-responsive region; EF: executive function (response-conflict)  
 181 region. Asterisks (\*) denote significant Bonferroni-corrected pairwise comparisons ( $p < 0.05$ ), Cross (†)  
 182 denote marginal difference ( $0.05 < p < 0.1$ ).

183 Next, we examined the developmental mechanism of lateralization differences across blind  
184 and sighted adults. Relative to sighted adults, secondary visual cortices of blind adults show a  
185 stronger dominance of within hemisphere connectivity. That is, left secondary visual  
186 networks are more strongly connected to left PFC networks, whereas right secondary visual  
187 networks are more strongly connected to right PFC (group (blind adults, sighted adults) by  
188 lateralization (within hemisphere, between hemisphere) interaction effect:  $F_{(1, 78)} = 131.51, p$   
189  $< 0.001$ ; post-hoc Bonferroni-corrected paired:  $t$ -test: sighted adults within hemisphere  $>$   
190 between hemisphere:  $t_{(49)} = 5.778, p < 0.001$ ; blind adults within hemisphere  $>$  between  
191 hemisphere:  $t_{(29)} = 10.735, p < 0.001$ ). Similar pattern were observed in primary visual  
192 cortex that blind adults show a stronger dominance of within hemisphere connectivity but  
193 there is no difference between the within and across hemisphere connectivity for sighted  
194 adults (group (blind adults, sighted adults) by ROI (within hemisphere, between hemisphere)  
195 interaction effect:  $F_{(1, 78)} = 87.211, p < 0.001$ ; post-hoc Bonferroni-corrected paired:  $t$ -test:  
196 sighted adults within hemisphere  $>$  between hemisphere:  $t_{(49)} = 3.251, p = 0.101$ ; blind  
197 adults within hemisphere  $>$  between hemisphere:  $t_{(29)} = 7.019, p < 0.001$ )(also see Kanjlia et  
198 al., 2021; Lane et al., 2017).

199  
200 The present evidence from sighted infants suggests that these adult-group differences in  
201 laterality reflect blindness-driven reorganization: Sighted infants resembled sighted adults  
202 more so than blind adults (Figure 3). There was a significant difference in laterality between  
203 blind adults and sighted infants (group (blind adults, infants) by ROI (within hemisphere,  
204 between hemisphere) interaction effect: second release:  $F_{(1, 355)} = 338.252, p < 0.001$ ; third  
205 release:  $F_{(1, 503)} = 303.04, p < 0.001$ ). There was no difference between sighted adults and  
206 sighted infants (group (sighted adults, infants) by ROI (within hemisphere, across  
207 hemisphere) interaction effect: second release:  $F_{(1, 375)} = 1.356, p = 0.245$ ; third release:  $F_{(1,$   
208  $523)} = 2.244, p = 0.135$ ; see supplementary results for a detailed group comparison of within  
209 and across hemisphere differences). Similar group by laterality interaction pattern are also  
210 observed in V1 (group (blind adults, infants) by ROI (within hemisphere, between  
211 hemisphere) interaction effect: second release:  $F_{(1, 355)} = 99.026, p < 0.001$ ; third release:  $F_{(1,$   
212  $503)} = 123.608, p < 0.001$ ; group (sighted adults, infants) by ROI (within hemisphere, across  
213 hemisphere) interaction effect: second release:  $F_{(1, 375)} = 5.486, p < 0.05$ ; third release:  $F_{(1, 523)}$   
214  $= 2.827, p = 0.093$ ). The incorporation of visual cortices into lateralized functional networks  
215 (e.g., language, response selection) in blindness may drive stronger within-hemisphere  
216 connectivity in this population (Kanjlia et al., 2021; Lane et al., 2017; Tian et al., 2022).

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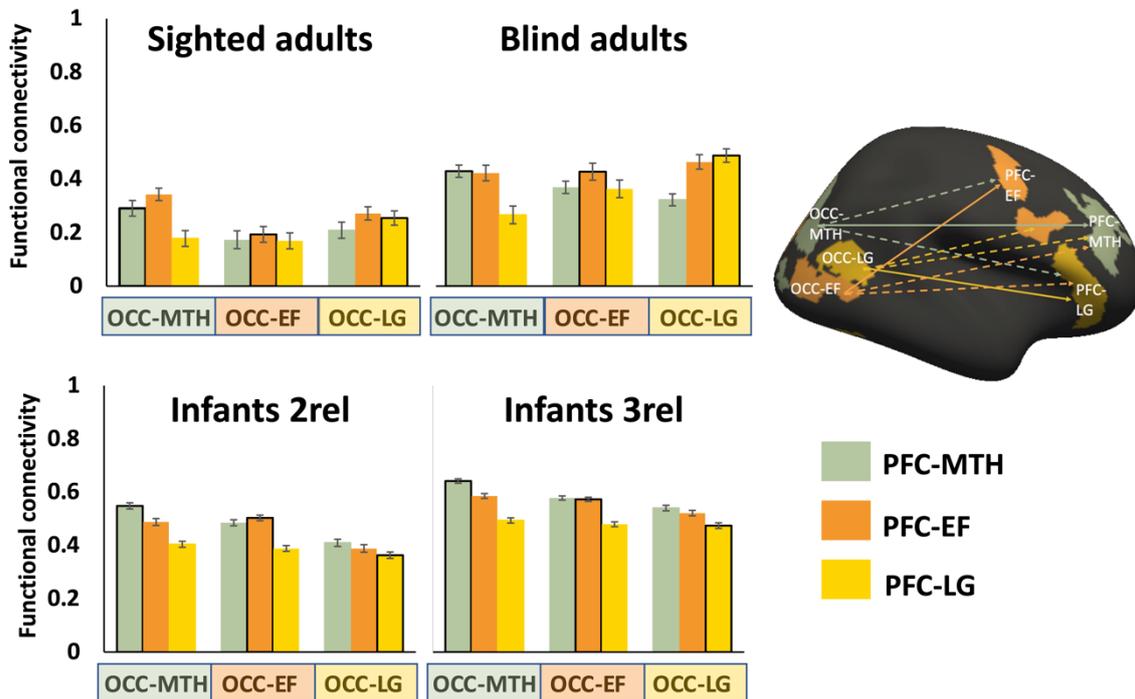
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219 **Figure 3** Within hemisphere (blue) vs. between hemisphere (orange) functional connectivity (r coefficient  
220 of resting state correlations) of secondary visual (left) and V1 (right) to prefrontal cortices in sighted  
221 adults, blind adults, and two cohorts of sighted infants (2<sup>nd</sup> and 3<sup>rd</sup> release of dHCP). Blind adults show a  
222 larger difference than any of the other groups.

223 Finally, we asked whether resting state patterns at birth could predict which prefrontal areas  
224 become coupled with which occipital regions, within hemisphere. In blind adults, resting  
225 state connectivity biases across different PFC areas align with specialization of task-based  
226 cross-modal responses within visual cortices (Abboud & Cohen, 2019; Amedi et al., 2003;  
227 Kanjlia et al., 2016, 2021). For example, language-responsive subregions of occipital cortex  
228 show strongest functional connectivity with language-responsive sub-regions of PFC,  
229 whereas math-responsive occipital areas show stronger connectivity with math-responsive  
230 PFC (Bedny et al., 2011; Kanjlia et al., 2016). Does the fronto-occipital functional  
231 connectivity specialization observed in adults exist in infancy and potentially drive task-  
232 based cross-modal specialization? We compared connectivity of three prefrontal and three  
233 occipital regions which were found to respond to language, arithmetic and response-conflict  
234 in previous cohorts of sighted (frontal) and blind (occipital and frontal) adults (Kanjlia et al.,  
235 2016, 2021; Lane et al., 2015).

236 Contrary to the hypothesis that fronto-occipital functional connectivity specialization is adult-  
237 like from birth, both cohorts of sighted infants showed a less differentiated fronto-occipital  
238 connectivity pattern relative to sighted and blind adults. Unlike in adults, in infants, all the  
239 occipital regions showed stronger correlations with math- and response-conflict related  
240 prefrontal areas than language-responsive prefrontal areas (Figure 4; occipital regions (math,  
241 language, response-conflict) by PFC regions (math, language, response-conflict) interaction:  
242 infants second release:  $F_{(4, 1304)} = 66.404, p < 0.001$ ; infants third release:  $F_{(4, 1896)} = 85.145, p$   
243  $< 0.001$ , post-hoc Bonferroni-corrected paired  $t$ -test see Supplementary Table S1). The  
244 occipital region that is sensitive to response-conflict in blind adults showed equivalent  
245 correlations with math and response-conflict PFC regions in infants. The region of occipital  
246 cortex that responds to language and shows the strongest connectivity with language  
247 responsive PFC in blind adults, showed stronger connectivity with math and response-  
248 conflict PFC areas in infants.

249 Although occipito-frontal connectivity was not adult-like in infants, biases in infants may  
250 relate to future differentiation: the preferential correlation with math responsive PFC was  
251 strongest in those occipital areas that go on to develop math responses in blind adults.  
252 Although the occipital region that is language-responsive in blind adults actually showed  
253 stronger connectivity to math and response-conflict areas of PFC in infants, this preference  
254 was smaller than the other two occipital ROIs examined, perhaps providing a less strong  
255 intrinsic bias to overcome.

256



257

258 **Figure 4** Occipito-frontal functional connectivity across different sub-regions of prefrontal (PFC) and  
 259 occipital cortex (OCC) in sighted adults, blind adults, and two cohorts of sighted infants. Sub-regions  
 260 (regions of interest) were defined based on task-based responses in a separate dataset of sighted (frontal)  
 261 and blind (frontal and occipital) adults (Kanjlia et al., 2016, 2021; Lane et al., 2015). PFC/OC-MTH math-  
 262 responsive regions were more active when solving math equations than comprehending sentences.  
 263 PFC/OC-LG language-responsive regions were more active when comprehending sentences than solving  
 264 math equations; EF: executive function (response-conflict) regions were more active during response  
 265 inhibition (no-go) trials than active go trials during an auditory no-go task (Kanjlia et al., 2016, 2021; Lane  
 266 et al., 2015). In blind adults (top right) these regions show biases in connectivity related to their function  
 267 i.e., language-responsive PFC is more correlated with language responsive OCC. No such pattern is  
 268 observed in infants. See supplementary material Figure S2 for connectivity matrix.

269 In sum, a comparison of resting state patterns in sighted infants, congenitally blind adults and  
 270 sighted adults provides evidence both for instructive effects of visual experience and  
 271 reorganizing effects of blindness on the development of functional connectivity in visual  
 272 cortices. Interestingly, we observed differences across the cortical hierarchy. The instructive  
 273 effects of visual experience were most clearly observed in secondary visual areas, where,  
 274 resting state connectivity patterns with non-visual networks in sighted infants resemble those  
 275 of blind adults more so than those of sighted adults. Vision appears to dampen functional  
 276 connectivity of secondary visual cortices with prefrontal networks and enhance connectivity  
 277 to non-visual sensory motor areas (i.e., A1 and S1/M1), possibly through synchronous multi-  
 278 modal experiences. In this respect, the sighted adult pattern, although the most common in  
 279 the population, is not the ‘default’ starting state but rather requires visual experience to  
 280 establish. In V1, the infants start at an intermediate point between sighted and blind adults.  
 281 There is a weak bias towards stronger connectivity with non-visual sensory-motor networks  
 282 which is strengthened by vision and reversed by blindness. The clearest example of  
 283 blindness-related change was observed in the case of laterality of connectivity between

284 occipital and prefrontal cortices, where sighted infants clearly resemble sighted adults. This  
285 suggests that strong lateralization of occipito-frontal connectivity is driven by blindness.

286 A key question for future research concerns the behavioral relevance of the observed  
287 connectivity patterns. For people who remain blind throughout life, the infant connectivity  
288 profile could play a role in enabling recruitment of visual cortices by non-visual functions  
289 e.g., high correlations between occipital and prefrontal networks might contribute to enabling  
290 responses of visual cortices to spoken and written language in congenitally blind adults.  
291 Conversely, in people who grew up blind but whose vision is restored in adulthood e.g.,  
292 through cataract removal or gene therapy, it will be important to determine the behavioral  
293 consequence of maintaining elements of the infant connectivity profile for visual perception  
294 and multi-modal integration, since some evidence suggests that (Ashtari, 2020)

## 295 **Method**

### 296 **Participants**

297 Fifty sighted controls and thirty congenitally blind individuals contributed the resting-state  
298 data (sighted  $N = 50$ ; 30 females; age:  $M = 35.33$ ,  $SD = 14.65$ ; years of education:  $M =$   
299  $17.08$ ,  $SD = 3.1$ ; blind  $N = 30$ ; 19 females; age:  $M = 44.23$ ,  $SD = 16.41$ ; years of education:  
300  $M = 17.08$ ,  $SD = 2.11$ ; blind vs. sighted age,  $t_{(78)} = 2.512$ ,  $p < 0.05$ ; blind vs. sighted years of  
301 education,  $t_{(78)} = 0.05$ ,  $p = 0.996$ ). Since blind participants were on average older, we also  
302 performed analyses in an age-matched subgroups of sighted controls and found similar results  
303 to the full sample (see Supplementary materials, Figure S3 to Figure S6). Blind and sighted  
304 participants had no known cognitive or neurological disabilities (screened through self-  
305 report). All adult anatomical images were read by a board-certified radiologist and no gross  
306 neurological abnormalities were found. All the blind participants had at most minimal light  
307 perception from birth. Blindness was caused by pathology anterior to the optic chiasm (i.e.,  
308 not due to brain damage). All participants gave written informed consent under a protocol  
309 approved by the Institutional Review Board of Johns Hopkins University.

310 Neonate data were from the second and third release of the Developing Human Connectome  
311 Project (dHCP) (<https://www.developingconnectome.org>). The Ethical approval was  
312 obtained from the UK Health Research Authority (Research Ethics Committee reference  
313 number: 14/LO/1169). The second release originally available data consists of images of 505  
314 neonatal subjects and the third release consists of images of 783 neonatal subjects.  
315 After quality control procedures (described below), 327 subjects in second release and 475  
316 subjects in third release were included in data analysis, with one scan per subject. The  
317 average age from birth at scan = 1.9 weeks; average gestational age (GA) at scan = 41.21  
318 weeks. We only included infants who were full-term or scanned at term-equivalent age if  
319 preterm (second release:  $n = 399$ ; third release:  $n = 607$ ). Infants with more than 160 motion  
320 outliers were excluded (second release:  $n=41$  dropped, third release:  $n = 89$  dropped). Motion-  
321 outlier volumes were defined as DVARS (the root mean square intensity difference between  
322 successive volumes) higher than 1.5 interquartile range above the 75th centile, after motion  
323 and distortion correction. Infants with signal drop-out in regions of interest (ROI) were also  
324 excluded (second release:  $n = 31$  dropped, third release:  $n = 43$  dropped). To identify signal  
325 dropout, we first averaged BOLD signal intensity by all the time point for each subject. From  
326 the time-averaged image, parcel-wise signals across the cortex were extracted using 100  
327 cortical parcel scheme defined by Schaefer's atlas (Schaefer et al., 2018). The intensity of the  
328 100 parcels gave the estimated distribution of the cortical BOLD signal. Likewise, the time-  
329 averaged BOLD intensities were extracted from the 16 ROIs used in the current study. For

330 each ROI, the signal dropout was identified when the BOLD intensity fell in extremely low  
331 end of the estimated BOLD signal distribution. In particular, signal intensities of 16 ROIs  
332 were transformed into z-scores using the MEAN and SD from the signal distribution of the  
333 100 cortical parcels. Thereby the signal dropout was identified as a z-scored BOLD intensity  
334 below -3. Participants were excluded if any of the ROIs showed a signal dropout.

### 335 **Image acquisition**

336 *Blind and sighted adult* MRI anatomical and functional images were collected on a 3T  
337 Phillips scanner at the F. M. Kirby Research Center. T1-weighted structural images were  
338 collected using a magnetization-prepared rapid gradient-echo (MP-RAGE) in 150 axial slices  
339 with 1 mm isotropic voxels. Resting-state fMRI data were collected in 36 sequential  
340 ascending axial slices for 8 minutes. TR = 2 s, TE = 0.03 s, flip angle = 70°, voxel size = 2.4  
341 × 2.4 × 2.5 mm, inter-slice gap = 0.5 mm, field of view (FOV) = 192 × 172.8 × 107.5.  
342 Participants completed 1 to 4 scans of 240 volume each (average scan time = 710.4 second  
343 per person). During the resting-state scan, participants were instructed to relax but remain  
344 awake. Sighted participants wore light-excluding blindfolds to equalize the light conditions  
345 across the groups during the scans.

346 *Neonate (dHCP)* Anatomical and functional images were collected on a 3T Phillips scanner  
347 at the Evelina Newborn Imaging Centre, St Thomas' Hospital, London, UK. A dedicated  
348 neonatal imaging 219 system including a neonatal 32-channel phased-array head coil was  
349 used. T2w multi-slice fast spin-echo images were acquired with in-plane resolution  
350 0.8x0.8mm<sup>2</sup> and 1.6mm slices overlapped by 0.8mm (TR = 12000 ms, TE = 156 ms, SENSE  
351 factor 2.11 axial and 2.6 sagittal). In neonates, T2w images were used as the anatomical  
352 image because the brain anatomy is more clearly in T2w than in T1w images. Fifteen minutes  
353 of resting-state fMRI data were collected using a used multiband (MB) 9x accelerated echo-  
354 planar imaging (TR = 392 ms, TE = 38ms, 2300 volumes, with an acquired resolution of 2.15  
355 mm isotropic). Single-band reference scans were acquired with bandwidth-matched readout,  
356 along with additional spin-echo acquisitions with both AP/PA fold-over encoding directions.

### 357 **Data analysis**

358 Resting-state data were preprocessed using FSL version 5.0.9 (Smith et al., 2004), DPABI  
359 version 6.1 (Yan et al., 2016) and in-house code ([https://github.com/NPDL/Resting-  
360 state\\_dHCP](https://github.com/NPDL/Resting-state_dHCP)). The functional data for all groups were linearly detrended and low-pass filtered  
361 (0.08 Hz).

362 For adults, functional images were registered to the T1-weighted structural images, motion  
363 corrected using MCFLIRT (Jenkinson et al., 2002), and temporally high-pass filtering (150  
364 s). No subject had excessive head movement (> 2mm) and rotation (> 2°) at any timepoint.  
365 Resting state data are known to include artifacts related to physiological fluctuations such as  
366 cardiac pulsations and respiratory-induced modulation of the main magnetic field. A  
367 component-based method, CompCor (Behzadi et al., 2007), was used to control for these  
368 artifacts. Particularly, following the procedure described in Whitfield-Gabrieli et al.  
369 (Whitfield-Gabrieli & Nieto-Castanon, 2012) nuisance signals were extracted from 2-voxel  
370 eroded masks of spinal fluid (CSF) and white matter (WM), and the first 5 PCA components  
371 derived from these signals was regressed out from the processed BOLD time series. In  
372 addition, a scrubbing procedure was applied to further reduce the effect of motion on  
373 functional connectivity measures (Power et al., 2012, 2014). Frames with root mean square

374 intensity difference exceeding 1.5 interquartile range above the 75th centile, after motion and  
375 distortion correction, were censored as outliers.

376 The neonate resting-state functional data were pre-processed by the dHCP group using the  
377 project's in-house pipeline (Fitzgibbon et al., 2020). This pipeline uses a spatial ICA-  
378 denoising step to minimize artifact due to multi-band artefact, residual head-movement,  
379 arteries, sagittal sinus, CSF pulsation. For neonates, ICA denoising is preferable to using  
380 CSF/WM regressors. It is challenging to accurately define anatomical boundaries of  
381 CSF/WM due to the low imaging resolution comparing with the brain size and the severe  
382 partial-volume effect in the neonate(Fitzgibbon et al., 2020). Like in the adults, frames with  
383 root mean square intensity difference exceeding 1.5 interquartile range above the 75th centile,  
384 after motion and distortion correction, were considered as motion outliers. Out from the 2300  
385 frames, a subset of continuous 1600 with minimum number of motion outliers was kept for  
386 each subject. Motion outliers were then censored from the subset, and a subject was excluded  
387 from further analyses when the number of outlier exceeded 160 (10% of the continues subset)  
388 (Hu et al., 2022).

389 From the preprocessed data, for both groups of adult and neonate, ROI-to-ROI connectivity  
390 was calculated using Pearson's correlation between ROI-averaged BOLD timeseries (ROI  
391 definition see below). All *t*-tests and *F*-tests are two-sided.

392

### 393 **ROI definition**

394 ROIs in the frontal and occipital cortices were defined from separate task-based fMRI  
395 experiments with blind and sighted adults (Kanjlia et al., 2016, 2021; Lane et al., 2015).  
396 Three experiments separate experiments were conducted with the same group of blind and  
397 sighted subjects (sighted n=18; blind n=23). The language ROIs in the occipital and frontal  
398 cortices were identified by sentence > nonwords contrast in an auditory language  
399 comprehension task (Lane et al., 2015). The math ROIs were identified by math > sentence  
400 contrast in an auditory task where participants judged equivalence of pairs of math equations  
401 and pairs of sentences (Kanjlia et al., 2016). The executive function ROIs were identified by  
402 no-go > frequent go contrast in an auditory go/no-go task with non-verbal sounds (Kanjlia et  
403 al., 2021). The occipital ROIs were defined based on group comparisons blind > sighted in a  
404 whole-cortex analysis. For example, the occipital language ROI were defined as the cluster  
405 that responded more to auditory sentence than auditory nonwords conditions in blind, relative  
406 to sighted, in a whole-cortex analysis. All three occipital ROIs were defined in the right  
407 hemisphere. Left-hemisphere occipital ROIs were created by flipping the right-hemisphere  
408 ROIs to the left hemisphere. The frontal ROIs were defined based on a whole-cortex analysis  
409 which combined all blind and sighted adult data. For example, the frontal language ROI was  
410 defined as responded more auditory sentence than auditory nonwords conditions across all  
411 blind and sighted subjects, constrained to the prefrontal cortex. For frontal ROIs, the  
412 language ROI was defined in the left, and the math and executive function ROI were defined  
413 in the right hemisphere, then flip to the other hemisphere. All the ROIs were defined based on  
414 group data and were converted into each subject's native space. Any overlapping vertices  
415 between ROIs were removed and not counted toward any ROIs.

416

417

418 **Data availability statement.**

419 Neonate data were from the second and third release of the Developing Human Connectome  
420 Project (dHCP) (<https://www.developing-connectome.org>). We are working on the IRB  
421 permission to publicly post the de-identified data. If and when permission is granted by IRB,  
422 we will release the de-identified data. The blind and sighted adults data is available upon  
423 request to Dr. Marina Bedny for now.

424

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