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*Research Article: New Research | Sensory and Motor Systems*

## **Active vision in sight recovery individuals with a history of long-lasting congenital blindness**

<https://doi.org/10.1523/ENEURO.0051-22.2022>

**Cite as:** eNeuro 2022; 10.1523/ENEURO.0051-22.2022

Received: 3 February 2022

Revised: 10 August 2022

Accepted: 17 August 2022

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*This Early Release article has been peer-reviewed and accepted, but has not been through the composition and copyediting processes. The final version may differ slightly in style or formatting and will contain links to any extended data.*

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1 **Active vision in sight recovery individuals with a history of long-lasting congenital blindness**

2 **Abbreviated Title:** Active vision despite congenital blindness

3 José P. Ossandón <sup>1\*</sup>, Paul Zerr <sup>1,2</sup>, Idris Shareef <sup>3</sup>, Ramesh Kekunnaya <sup>3</sup>, Brigitte Röder <sup>1</sup>

4 <sup>1</sup> Biological Psychology and Neuropsychology, Hamburg University, Hamburg, Germany

5 <sup>2</sup> Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands

6 <sup>3</sup> Child Sight Institute, Jasti V Ramanamma Children's Eye Care Center, LV Prasad Eye Institute,

7 Hyderabad, India

8 **Author contributions:** J.P.O and B.R. designed the research; R.K. and I.S identified and evaluated the  
9 clinical population; J.P.O., I.S. and P.Z. performed the research; J.P.O analyzed the data; J.P.O and B.R  
10 wrote the paper; all authors edited and approved the manuscript.

11 Correspondence should be addressed to José P. Ossandón, [jose.ossandon@uni-hamburg.de](mailto:jose.ossandon@uni-hamburg.de)

12

13 Number of Figures: 4                      Number of Tables: 1

14 Number of Multimedia: 1                Number of words for Abstract: 182

15 Number of words for Significance Statement: 118

16 Number of words for Introduction: 747

17 Number of words for Discussion: 1936

18

19 **Acknowledgments:** The authors are grateful to D. Balasubramanian who made the research at the LV  
20 Prasad Eye Institute possible. We thank Kabilan Pitchaimuthu and Prativa Regmi for clinical data curation  
21 and Suddha Sourav and Rashi Pant for technical support.

22 **Conflict of Interest:** Authors report no conflict of interest.

23 **Funding sources:** This work was supported by the German Research Foundation (DFG) (grants Ro  
24 2625/10-1 and SFB936 – 178316478 - B11).

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27 **Active vision in sight recovery individuals with a history of long-**  
28 **lasting congenital blindness**

29

30 **ABSTRACT**

31 What we see is intimately linked to how we actively and systematically explore the world through  
32 eye movements. However, it is unknown to what degree visual experience during early  
33 development is necessary for such systematic visual exploration to emerge. The present study  
34 investigated visual exploration behavior in ten human participants whose sight had been restored  
35 only in childhood or adulthood, after a period of congenital blindness due to dense bilateral  
36 congenital cataracts. Participants freely explored real-world images while their eye movements  
37 were recorded. Despite severe residual visual impairments and gaze instability (nystagmus),  
38 visual exploration patterns were preserved in individuals with reversed congenital cataract.  
39 Modelling analyses indicated that similar to healthy controls, visual exploration in individuals  
40 with reversed congenital cataract was based on the low-level (luminance contrast) and high-level  
41 (object components) visual content of the images. Moreover, participants used visual short-term  
42 memory representations for narrowing down the exploration space. More systematic visual  
43 exploration in individuals with reversed congenital cataract was associated with better object  
44 recognition, suggesting that active vision might be a driving force for visual system development  
45 and recovery. The present results argue against a sensitive period for the development of neural  
46 mechanisms associated with visual exploration.

47

48 **SIGNIFICANCE STATEMENT**

49 Humans explore the visual world with systematic patterns of eye movements, but it is unknown  
50 whether early visual experience is necessary for the acquisition of visual exploration. Here, we  
51 show that sight recovery individuals who had been born blind demonstrate highly systematic eye  
52 movements while exploring real-world images, despite visual impairments and pervasive gaze  
53 instability. In fact, their eye movement patterns were predicted by those of normally sighted  
54 controls and models calculating eye movements based on low- and high-level visual features, and  
55 they moreover took memory information into account. Since object recognition performance was  
56 associated with systematic visual exploration it was concluded that eye movements might be a  
57 driving factor for the development of the visual system.

## 58 INTRODUCTION

59 Prolonged visual deprivation from birth has been observed to result in the irreversible impairment  
60 of several visual functions (Lewis and Maurer, 2005; Röder and Kekunnaya, 2021a). These  
61 findings have been taken as evidence for “sensitive periods” in brain development, defined as  
62 epochs during which adequate input is essential for full functional development (Knudsen, 2004;  
63 Hensch, 2005). In humans, sensitive periods have been studied in individuals who had been born  
64 blind or with severe visual impairments due to dense, bilateral cataracts and who later received  
65 cataract-removal surgery at different times during infancy, childhood or even adulthood (Maurer  
66 et al., 2007; Röder et al., 2013; Ganesh et al., 2014). Despite improvements in vision after  
67 congenital cataract removal (Wright et al., 1992), basic visual abilities such as visual acuity  
68 (Elleberg et al., 1999; Lambert et al., 2006) remain permanently impaired, especially if cataracts  
69 are not treated within the first few weeks of life. Moreover, higher order visual functions such as  
70 feature binding and within-category viewpoint-independent discrimination, particularly of faces,  
71 have been found to only partially recover after congenital cataract surgery, and not to the degree  
72 expected by the recovery of visual acuity (Le Grand et al., 2001; Putzar et al., 2007, 2010;  
73 Ostrovsky et al., 2009). In addition to these perceptual deficits, individuals who had prolonged  
74 congenital bilateral visual deprivation (>8 weeks) typically also suffer from nystagmus (Rogers et  
75 al., 1981; Lambert et al., 2006; Birch et al., 2009). Nystagmus is a disorder of gaze stability that  
76 results in continuous, periodic and involuntary motion of the eyes.

77       It has recently been shown that despite some distortions due to the superimposed  
78 nystagmus, eye movements to simple visual stimuli were reasonably precise and fast in  
79 individuals with reversed congenital cataract (Zerr et al., 2020). However, it is unclear whether  
80 higher levels of ocular control, such as the ability to generate typical patterns of active visual  
81 exploration of natural stimuli, recover after a transient phase of congenital visual deprivation.  
82 Active visual exploration is crucial for visual functions such as visual search and object

83 identification, especially in noisy or ambiguous conditions (Einhauser et al., 2004; Holm et al.,  
84 2008; Kietzmann et al., 2011). Furthermore, active visual exploration has been shown to be  
85 relevant for visual memory formation in typically sighted individuals (Hannula, 2010).

86 Previous research has suggested that visual exploration is guided by both bottom-up  
87 (stimulus-driven) and top-down mechanisms, which jointly define the direction towards which the  
88 eyes move. Stimulus-driven mechanisms use input characteristics such as luminance, color,  
89 orientation and motion (Veale et al., 2017); whereas top-down mechanisms consider goals,  
90 memory, and contextual factors (Eckstein, 2011; Tatler et al., 2011; König et al., 2016). Stimulus-  
91 driven “saliency” models have successfully utilized low- and high-level visual features to predict  
92 human eye movements during free-viewing of scenes (Itti and Koch, 2000; Tatler et al., 2005;  
93 Kümmerer et al., 2017). Additionally, the repeated presentation of the same image has been used  
94 to assess the effects of short-term memory on visual exploration, that is, a non-reflexive aspect of  
95 gaze control (Ryan et al., 2000; Smith et al., 2006; Kaspar and König, 2011). If an image is  
96 repeatedly encountered, the spread of visual exploration decreases (Hannula, 2010). It has been  
97 hypothesized that short-term memory representations provide top-down information, which,  
98 combined with bottom-up stimulus-driven maps in so called priority maps, guide eye movements  
99 (Veale et al., 2017).

100 The degree to which the development of bottom-up and top-down mechanisms of active  
101 visual exploration depend on typical visual input after birth is unknown. Theories from  
102 developmental psychology have suggested that active visual exploration in infants is instrumental  
103 for the development of object knowledge (Johnson and Johnson, 2000). It remains to be  
104 investigated whether visual recovery after late sight restoration affects bottom-up, stimulus-driven  
105 visual exploration (Einhäuser et al., 2008a; Açıık et al., 2009; Nuthmann and Henderson, 2010),  
106 and/or top-down, for instance, memory based visual exploration (Hannula, 2010).

107            In the present study, we employed a free-viewing task in a sample of 10 individuals who  
108 had been born with dense, bilateral cataracts which had been surgically removed later in life (CC  
109 group, see Table 1) - in some participants, only in late childhood or adulthood. The distribution of  
110 gazed locations elicited by photographic stimuli (close-up images of different objects, plants,  
111 animals and buildings) were assessed and compared to the typical visual exploration patterns of  
112 age-matched, normally sighted controls (SC group). Further, the CC group was compared to  
113 individuals with nystagmus due to reasons other than congenital cataracts (nystagmus controls,  
114 NC group), and individuals with a history of developmental cataracts (developmental cataract  
115 reversal group, DC group), in order to isolate group differences specific to early visual  
116 deprivation rather than a general history of visual deficits. Additionally, we tested how well visual  
117 exploration in individuals with reversed congenital cataract was predicted by low- and high-level  
118 saliency models. Finally, to explore top-down influences on visual exploration, the effects of  
119 short-term memory on eye movements were assessed by assessing the adaptation of visual  
120 exploration patterns for images which were repeatedly presented.

**Table 1: Participants description**

	Age at testing in years	Age at surgery in months	Cataract type at surgery	Presurgical visual acuity (best eye)	Most recent visual acuity (CC/DC: postsurgical) (best eye)		Cataract Family history
					Decimal	logMAR	
<b>Congenital cataract group (CC, N = 10)</b>							
cc-1	16.9	4	dense	FFL+	0.33	0.47	no
cc-2	13.5	83	absorbed	CF 3m	0.15	0.79	no
cc-3	31.7	168	absorbed	unknow	0.1	1	yes
cc-4	42.9	264	absorbed	0.06 (decimal)	0.16	0.79	yes
cc-5	16.1	186	absorbed	0.03 (decimal)	0.08	1.1	no
cc-6	12.3	138	dense	CF CF	0.03	1.4	yes
cc-7	21.7	213	dense	CF 0.5m	0.12	0.9	yes
cc-8	10.7	17	dense	PL at 0.5m	0.25	0.6	no
cc-9	23.5	3	dense	FFL-	0.25	0.6	no
cc-10	17.2	34	dense	FFL+	0.16	0.79	no
<b>summary</b>	M:20.7 R:10 – 42	M:111 (9.2 years) R: 4 – 264			GM: 0.14 R: 0.03 – 0.3	M: 0.86 R: 0.47 – 1.4	
<b>Developmental cataract control group (DC, N = 9)</b>							
dc-1	24.4	31	not dense	FFL +	0.5	0.3	no
dc-2	13.8	89	dense	CF 1 m	0.66	0.17	unknown
dc-3	16.2	130	not dense	0.4	0.8	0.09	no
dc-4	13.2	71	dense	FFL +	0.46	0.33	unknown
dc-5	17.3	91	not dense	0.16	0.8	0.09	unknown
dc-6	11.5	91	not dense	0.25	0.8	0.09	unknown
dc-7	18.8	208	not dense	0.2	0.7	0.13	no
dc-8	11.6	54	dense	CF 1 m	1	0	unknown
dc-9	13.5	30	dense	FFL +	0.66	0.17	unknown
<b>summary</b>	M:15.6 R:11 – 24	M: 88.3 (7.4 years) R: 30 – 208	4 dense		GM: 0.7 R: 0.46 – 1	M: 0.16 R: 0 – 0.33	
<b>Nystagmus control group (NC, N = 10)</b>							
<b>summary</b>	M:15 R: 8 – 37				GM: 0.45 R: 0.25 – 0.8	M: 0.35 R: 0.1 – 0.6	
<b>Normally sighted control group (SC, N = 13)</b>							
<b>summary</b>	M: 23.7 R: 11 – 40				1 (all)	0 (all)	

PL: perception light; CF: counting finger, equivalence with logMAR acuity has been reported to be 1.7-2.0 at 30 cm (Schulze-Bonsel et al., 2006); CF CF: counting finger close to face; FFL: fixate and follows light; M: mean; GM: geometric mean, R: range.

Extended data Table 1-1 shows the relationship between visual acuity and age of surgery (CC and DC groups) and age of testing (all groups).

121

122



## 123 MATERIALS AND METHODS

### 124 Participants

125 A total of 42 participants from four different populations were recruited at the LV Prasad Eye  
126 Institute and the local community of Hyderabad (India).

127 (1) Congenital cataract reversal individuals (CC group): Individuals were selected from a  
128 large number of patients who had been treated with the diagnosis of congenital cataracts. Based  
129 on medical records, a clinical history of bilateral congenital cataracts and a history of patterned  
130 visual deprivation were confirmed. A lack of fundus view and a lack of retinal glow were  
131 considered as evidence for the absence of patterned input reaching the retina prior to cataract  
132 surgery. Additionally, the presence of nystagmus, sensory strabismus, positive family history as  
133 well as absorbed lenses aided in the classification of CC participants.

134 The CC group consisted of 10 participants (2 females; mean age: 20.7 years; range: 10.7 –  
135 42.9) who had received cataract removal surgery at a mean age of 9.2 years (range: 3 months – 22  
136 years). These individuals were tested on average 11.4 years after cataract removal surgery (range:  
137 7 months – 23.2 years). Of the 10 participants, 5 had a documented history of strabismus (2  
138 esotropia/3 exotropia), 7 had implanted intraocular lenses, and the remaining 3 used corrective  
139 glasses. Four CC individuals had a documented family history of congenital cataracts, and 4 CC  
140 individuals had absorbed cataracts when presented at the LV Prasad Eye Institute. Absorption of  
141 cataracts in middle to late childhood has been regularly observed in individuals born with dense  
142 congenital cataracts. Absorbed cataracts can be unambiguously differentiated from non-dense or  
143 partial cataracts by, for instance, the morphology of the lens, anterior capsule wrinkling, as well  
144 as plaque or thickness of the stroma. Absorbed cataracts strongly imply dense cataracts, and  
145 therefore blindness, at birth. Pre-surgical visual acuity measurements in severely visually  
146 deprived individuals confirmed that at least 7 out of 10 CC individuals were blind (i.e. had a  
147 visual acuity of less than 3/60) (World Health Organization, 2019). The remaining three CC

148 individuals had absorbed lenses; their pre-surgery vision corresponded to severe visual  
149 impairment, as defined by the WHO. All CC participants additionally suffered from nystagmus,  
150 which is strong evidence for the absence of patterned vision at birth. CC participants' post-  
151 surgical visual acuity of the better eye ranged from 0.03 to 0.33 decimal units (geometric mean:  
152 0.14; logMar: 0.47 – 1.4, logMar mean: 0.86). A detailed description of CC participants is  
153 presented in Table 1 (and Extended data Table 1-1).

154 (2) Developmental cataract reversal group (DC group): This control group allowed us to  
155 estimate the role of vision at birth for the acquisition of visual exploration behavior. The DC  
156 group consisted of nine individuals (4 females, mean age: 15.6 years, range: 11.6 – 24.4) with a  
157 history of bilateral cataracts, but not dense and/or congenital cataracts. These individuals allowed  
158 us to control for task independent effects on eye movements due to cataract surgery (e.g.,  
159 exploring the images with intraocular lenses). Cataract removal surgery had been performed at a  
160 mean age of 7.4 years (range: 2.8 – 17.3 years); they were tested on average 8.2 years (range: 1.5  
161 – 21.8 years) post-surgery. DC participants' post-surgical visual acuity ranged from 0.46 to 1  
162 decimal units (geometrical mean: 0.7; logMar: 0 – 0.33, logMar mean: 0.16). All DC participants  
163 were fitted with intraocular lenses.

164 Retrospective classification of CC and DC participants comes with some degree of  
165 uncertainty. However, the use of the classification criteria as implemented in the present study  
166 have recently been confirmed by an electrophysiological biomarker (Sourav et al., 2020).

167 (3) Nystagmus group (NC group): To disentangle the effects of congenital visual  
168 deprivation from the effects of prevailing sensory nystagmus, which was present in all CC  
169 participants, individuals with nystagmus due to conditions other than congenital cataracts were  
170 tested as additional controls. Individuals in this group did not have experience a phase of severe  
171 visual deprivation. Therefore, this group allowed us to distinguish which changes in visual  
172 exploration behavior can be attributed to the effects of nystagmus vs congenital visual

173 deprivation. This group comprised of 10 participants (1 female, mean age: 15.0 years, range: 8.7 –  
174 37.3) with Infantile Nystagmus syndrome (9 idiopathic, 1 oculocutaneous albinism), without a  
175 history of cataracts, severe visual impairment or blindness. NC participants' visual acuity ranged  
176 from 0.25 to 0.8 decimal units (geometrical mean: 0.45; logMar: 0.1 – 0.6, logMar mean: 0.35).

177 (4) The sighted control group (SC group) consisted of 13 individuals (3 females, mean  
178 age: 23.7 years, range: 11.2 – 40.6) with normal or corrected-to-normal vision. This group was  
179 partially age-matched to the CC group (no significant difference in age at testing,  $t_{(21)} = -0.84$ ,  $p =$   
180 0.41). The SC group allowed us to establish typical eye movement parameters for healthy  
181 individuals, in the current experimental setting and for the employed images.

182 All individuals were tested at the LV Prasad Eye Institute. None of the participants had  
183 any other sensory deficit or neurological disorder, diagnosed or self-reported. Expenses associated  
184 with taking part in the study were reimbursed. Minors additionally received a small present.  
185 Participants, and if applicable, their legal guardians, were informed about the study and received  
186 the instructions in one of the languages they were able to understand (in most cases Telegu,  
187 Hindi, or English). All participants gave written informed consent before participating in the  
188 study; in case of minors, legal guardians additionally provided informed consent. The study was  
189 approved by the ethics board of the Faculty of Psychology and Human Movement Science of the  
190 University of Hamburg (Germany) and by the ethics board of the LV Prasad Eye Institute.

191

## 192 **Stimuli**

193 Forty-nine images from the Natural Face and Object Stimuli image set were used in this study  
194 (Rossion et al., 2015) ([https://face-categorization-lab.webnode.com/resources/natural-face-](https://face-categorization-lab.webnode.com/resources/natural-face-stimuli/)  
195 [stimuli/](https://face-categorization-lab.webnode.com/resources/natural-face-stimuli/)). The images displayed objects representing 7 different categories: animals, chairs, fruits,  
196 guitars, houses, plants, and telephones. Objects were located close to the center of the image.  
197 Images were displayed in gray scale at an 800 x 800 pixel resolution, subtending 19.6 x 19.6

198 visual degrees. Stimuli were generated in MATLAB (The MathWorks, Natick, MA) using  
199 Psychtoolbox 3 (Brainard, 1997; Kleiner et al., 2007) on a Windows 7 PC and presented with an  
200 24" Eizo FG2421 LCD monitor at a resolution of 1920 x 1080 @ 120 Hz.

201         Due to copyright concerns, the figures shown here use line drawings of the actual images  
202 presented during the experiment.

203

#### 204 **Eye-tracking and calibration**

205 Eye movements were recorded with a video-based binocular eye-tracking system at 500 Hz  
206 (Eyelink1000 Plus, SR Research Ltd, Canada). Subjects were seated in a darkened room and  
207 placed their heads on a chin rest such that their eyes were at a distance of 60 cm from the screen.  
208 Due to several participants presenting nystagmus, it was not possible to use the built-in standard  
209 online calibration method of the eye-tracker system. Instead, a custom-made calibration routine  
210 was employed. This calibration routine used 5 screen positions as points (presented at the screen  
211 center, 15° right and left of the center and 8.5° above and below the center). Each participant was  
212 asked to look at these 5 points. Next, the screen center position was displayed again, in order to  
213 estimate calibration error. The experimenter manually controlled the calibration. During the  
214 presentation of each calibration position, the experimenter decided whether an eye movement was  
215 performed to the corresponding point and selected low-velocity periods of the nystagmus at each  
216 calibration point. These low-velocity periods typically follow the corrective saccade of the  
217 nystagmus, that is, they are aligned with the target position. The online calibration was performed  
218 to visually confirm that calibration points aligned with the 5 position patterns. This confirmation  
219 was necessary to decide whether the procedure had to be repeated, or if the calibration was  
220 sufficiently precise to continue. During offline calibration, low velocity periods of nystagmus  
221 were selected as described for online calibration.

222 The median positions of the selected gaze samples were fitted with a polynomial function  
223 (Stampe, 1993) to the corresponding screen positions. This is the same algorithm as the one  
224 implemented in the Eyelink eye-tracker software. The same calibration procedure was applied to  
225 all participants irrespective of whether they suffered from nystagmus or not. Calibration error was  
226 calculated only for the central position of the screen, and did not differ between groups (robust  
227 linear model contrasts, all contrasts  $p > 0.05$ ; mean CC group:  $0.83^\circ$ , SD: 0.95; mean SC group:  
228  $0.31^\circ$ , SD: 0.12; mean DC group:  $0.59^\circ$ , SD: 0.37; mean NC group:  $0.78^\circ$ , SD: 0.83).

229 A certain proportion of gaze data was missing when the gaze fell outside of the image, or  
230 during periods when the eye tracker lost the pupil. On an average, 9.9% of CC participants' gaze  
231 data were missing, compared to 3.69% for SC, 4.27% for DC, and 9.93% for NC participants.

232 To guarantee a sufficiently reliable estimate, only the visual exploration data from images  
233 with at least 50% valid recordings (i.e., gaze location values within the image) were included for  
234 analyses. Under this criterion, 7, 1, 1, and 6 image explorations had to be disregarded for the CC,  
235 SC, DC and NC group, respectively. In total, we discarded less than 0.6% of the data.

### 236 **Procedure**

237 After the calibration was completed, the experiment was carried out in 2 blocks of 14 trials each.  
238 A trial consisted of 2 images presented sequentially. Each trial started with a white fixation dot  
239 (diameter  $\sim 1.8^\circ$ ) presented in the center of the screen for 1 s, followed by the presentation of the  
240 first image for 4 s. Next, a central white fixation dot was shown a second time for 1 s which was  
241 followed by the presentation of the second image for 4 s. Participants were instructed to visually  
242 explore the images, and report the names of the objects they had encountered in the two images at  
243 the end of the trial. After participants provided the names of the two images, the experimenter  
244 decided whether each image was correctly named. The experimenters knew about the possible  
245 categories and were instructed to accept responses at the exemplar level (e.g. banana) and  
246 categorical level (e.g. fruit).

247 In 7 of the 28 trial image pairs, the same image was presented as the first and second  
248 image. In another 7 trial pairs, the two images were different, but from the same object category.  
249 In the remaining 14 trial pairs, the images were from different categories. Image presentation  
250 order was randomized across subjects with respect to pair type (repeated image, repeated  
251 category, different category). Order of presentation within a pair in the repeated- and different  
252 category pairs was randomized across subjects. The experiment took around 15-20 min,  
253 depending on the duration of the eye-tracker calibration procedure.

254

### 255 **Data analysis and statistics**

256 The common procedure in eye-tracking research is to use fixation positions as the unit of analysis.  
257 However, the nystagmus of the CC and NC individuals made it impossible to define fixations by  
258 employing typical velocity and acceleration thresholds. Hence, the dependent variables for all  
259 participants were calculated with respect to the position of all eye-tracking data samples  
260 (subsequently referred to as “gaze” data, obtained at a 500 Hz sampling rate). Several studies  
261 have shown that individuals with nystagmus gather information during the complete period of the  
262 nystagmus, and not only during the low-velocity phase (Jin et al., 1989; Goldstein et al., 1992;  
263 Waugh and Bedell, 1992; Dunn et al., 2014). Therefore, for uniformity of the analysis across  
264 groups, all gaze data were used, including high-velocity samples which would normally be  
265 considered saccades.

266

### 267 *Instantaneous Gaze Velocity*

268 The extent of gaze instability in all participants was estimated by deriving “instantaneous gaze  
269 velocity”. Usually, gaze velocity is calculated from multiple samples to remove high frequency  
270 noise inherent to oculomotor recordings (Stampe, 1993; Holmqvist et al., 2011). In the present  
271 study, we employed a modified version of the 2-point central difference algorithm (Bahill et al.,

272 1982) that is standard in the literature (e.g., Engbert, 2003; Dimigen et al., 2009; Otero-Millan et  
 273 al., 2014), and used as the default by the EyeLink eye-tracker (SR Research, 2019). For a sample  
 274 point  $n$ , the corresponding instantaneous gaze velocity (visual degrees per second, °/s), is defined  
 275 as the sum of 6 non-consecutive eye-tracking gaze samples (position in screen pixels):

$$Velocity_{(n)} = \frac{SR \times (gaze_{(n+4)} + gaze_{(n+3)} + gaze_{(n+2)} - gaze_{(n-2)} - gaze_{(n-3)} - gaze_{(n-4)})}{18 \times PPD}$$

276 SR is the eye-tracker sampling rate (500 Hz), PPD the pixels-per-degree resolution (~ 40.6), and  
 277 18 corresponds to the sum of the number of samples in the intervals used in the calculation (  
 278  $(4--4) + (3--3) + (2--2)$ ). This calculation was done separately for the horizontal and  
 279 vertical eye movement components.

280

### 281 Entropy

282 To assess the spread or dispersion of visual exploration, the informational entropy of the spatial  
 283 distribution of gazed locations was calculated for each image and participant (Açık et al., 2010;  
 284 Wilming et al., 2011; Shiferaw et al., 2019). Informational entropy is defined as the average  
 285 amount of information of a random variable. Entropy is higher when uncertainty of an outcome is  
 286 high and thus when events carry relatively more information. Entropy is maximal for variables  
 287 with a uniform distribution. In terms of visual exploration patterns, a higher spread or a broader  
 288 spatial distribution of gazed locations results in higher entropy. Conversely, a narrow spatial  
 289 distribution results in lower entropy values.

290 To calculate entropy values for each subject and image, first, a discrete spatial distribution  
 291 of gazed locations was constructed by dividing each image into a 20 x 20 matrix of 2° x 2° cells.

292 Next, we counted how many times each cell was gazed at by a given participant. Finally, the

293 entropy value of each spatial distribution was calculated by:  $H(P) = -\sum_{i=1}^n \frac{p_i^{CS} * \log_2(p_i^{CS})}{Coverage(p_i^{CS})}$ ,

294 where  $p_i^{cs}$  is the probability of gazing at a given cell. Coverage is a correction term suggested by  
295 Chao and Shen (2003) as a modification of the original entropy formula of Shannon in order to  
296 avoid biases due to limited sampling (Wilming et al., 2011).

297 In order to confirm the robustness of the results, entropy values were additionally  
298 calculated based on gaze distributions for a smaller ( $1^\circ \times 1^\circ$ ) and larger ( $4^\circ \times 4^\circ$ ) cell size. Results  
299 did not differ, and thus we report the results based on a cell size of  $2^\circ \times 2^\circ$ .

300

### 301 *Predictor maps for visual exploration patterns*

302 We evaluated how well each participant's exploration patterns were explained by (1) the  
303 exploration pattern of other participants; (2) by the low-level features; and (3) by the high-level  
304 visual features of the presented images. Three different predictor maps were correspondingly  
305 generated: (1) the visual exploration pattern for each image as assessed in the SC control group;  
306 (2) images' low-level Intensity Contrast Feature (ICF) model (Kümmerer et al., 2017); and (3)  
307 images' high-level feature map as defined by the DeepGaze II (DG-II) model (Kümmerer et al.,  
308 2016).

309 The first predictor was derived from the empirical distribution of gaze locations across all  
310 participants of the SC group. A two-dimensional spatial probability distribution was constructed  
311 for each image by pooling all the gaze eye-tracking samples of SC individuals for each image. For  
312 predictions within the SC group, the SC predictor map was constructed in a leave-one-out cross-  
313 validation procedure. Pixel-level gaze counts were spatially smoothed with a two-dimensional  
314 Gaussian unit kernel (full width at half maximum = 2 degrees) and normalized by dividing by the  
315 total count of gaze samples.

316 The second predictor map, ICF, consisted of a two-dimensional spatial distribution  
317 constructed based on the images' low-level features (luminance contrast). Different low-level



318 features are known to be highly correlated (Onat et al., 2014), and simple models based on  
319 contrast features seem to perform as well as more complex models that include multiple low-level  
320 visual features (Kienzle et al., 2009). Thus, we used a low-level model based solely on luminance  
321 contrast.

322 The third predictor map, DG-II, consisted of a two-dimensional spatial distribution  
323 constructed based on features derived by a deep neural network optimized for object recognition  
324 (Simonyan and Zisserman, 2014). The DeepGaze II model is currently considered the best  
325 performing model for free viewing according to the MIT Saliency Benchmark 2019  
326 (<http://saliency.mit.edu>). The DG-II model selects local features that serve as a basis for object  
327 classification, but it does not segment or tag objects. Note that the DG-II model typically  
328 performs the best at predicting eye-movement behavior for images depicting text or faces, which  
329 our stimuli dataset did not include. Nevertheless, the DG-II model has been shown to outperform  
330 the ICF model even in the absence of such features (Kümmerer et al., 2017).

331 ICF and DG maps were computed for each image using the python code made available  
332 by Matthias Kümmerer and the Bethge Lab (<https://deepgaze.bethgelab.org>). ICF and DG maps  
333 were generated for each original image, as well as for three low-pass filtered image versions. The  
334 latter were obtained by filtering the images using a 2D Gaussian kernel with frequency cutoffs  
335 (0.67 reduction) at 0.5, 1, and 2 visual degrees, respectively.

336

337 *Area under the curve (AUC)*

338 To determine how well a given predictor map explained participants' visual exploration patterns,  
339 we tested whether the values of the predictor map allowed a classification of image locations as  
340 gazed versus non-gazed. For non-gazed locations, values were taken from gazed locations in other  
341 images by the same participant. This procedure to define non-gazed locations was introduced to  
342 avoid an inflated classification success due to possible spatial biases (Tatler et al., 2005; Wilming

343 et al., 2011; Bylinskii et al., 2016), in both humans visual exploration patterns and photographic  
344 image features (Tatler et al., 2005; Tatler, 2007; Einhäuser et al., 2008b). For each participant,  
345 gazed and non-gazed values were pooled across images. These values were used to estimate the  
346 classification success of a predictor map by calculating the Area Under the Curve (AUC) of the  
347 receiver operator characteristic curve (Green and Swets, 1988; Fawcett, 2006). AUC values can  
348 be calculated by first taking the Mann-Whitney  $U$  statistic (also called Wilcoxon rank-sum test)  
349 between gazed and non-gazed values of the predictor map:

350  $U = R_{gazed} - n_{gazed}(n_{gazed} + 1)/2$ , where  $n_{gazed}$  is the sample size of gazed locations and  
351  $R_{gazed}$  is the sum of ranks in the sample of gazed location, obtained by assigning a numeric rank  
352 to every gazed and non-gazed values, beginning with 1 for the smallest value. AUC values are  
353 directly derived from  $U$  by normalizing with the product of the number of gazed and non-gazed  
354 locations (Bamber, 1975):

355  $AUC = U/(n_{gazed} * n_{non\_gazed})$ . AUC values range between 0 and 1, with 0.5 corresponding to  
356 chance discrimination and 1 indicating perfect classification. In some analyses, AUC values were  
357 obtained per image rather than per subject: gazed and non-gazed values were pooled across  
358 participants for each image instead across images for each participant.

359 To further control for any additional potential analyzing bias, control AUC values were  
360 calculated as follows: instead of using the predictor map for a given image, images were shuffled,  
361 that is, the predictor map of another randomly selected image was used to predict visual  
362 exploration of a given image.

363

#### 364 *Statistical tests*

365 Group differences in instantaneous gaze velocity, entropy and AUC values were evaluated with  
366 robust linear regression models using a categorical group factor. The models employed an

367 iteratively reweighted least square method using a bi-square weight function as implemented in  
368 the MATLAB R2019b function *fitlm* (Holland and Welsch, 1977). As there were 6 possible  
369 between-group comparisons, group contrasts were tested at a Bonferroni-corrected significance  
370 level of 0.05/6.

371 Moreover, AUC values for the SC, ICF and DG-II predictor maps were evaluated for  
372 different time periods after image presentation. This analysis tested whether classification success  
373 depended on the phase of visual exploration. AUC values were computed from data partitions  
374 obtained by dividing each participant's gaze data into 8 non-overlapping 500 ms intervals, from  
375 the beginning to the end of the trial. These sets of AUC values, excluding the first interval, were  
376 entered in a linear mixed-effects model with group as a categorical factor, a time-interval  
377 covariate as a fixed effect (7 levels), and participant identity as a random effect.

378 In the CC and NC groups, we additionally evaluated differences in AUC values generated  
379 from gaze locations, obtained by dividing each participant's gaze data into ten bins according to  
380 the magnitude of instantaneous gaze velocity. This analysis tested whether classification success  
381 of the SC predictor map depended on gaze stability in the CC and NC group. The new set of AUC  
382 values were entered in a linear mixed-effects model with group as a categorical factor, a velocity  
383 quantile covariate as a fixed effect, and participant identity as a random effect.

384 To assess the effects of short-term memory on visual exploration patterns, the repetition  
385 effect was evaluated by comparing the entropy values between the first and the second image of  
386 trial pairs. Entropy values for each image were entered in a linear mixed-effects model, with  
387 participant group (4 levels: CC, SC, DC, NC) and image order within a pair (2 levels: 1<sup>st</sup> or 2<sup>nd</sup>) as  
388 fixed effect predictors, and participant identity as a random effect. This analysis was done  
389 separately for each type of trial pair (repeated identity, repeated category, unrelated new image).

390 Linear mixed-effect models were calculated in R (version 3.6.3), using restricted  
391 maximum likelihood estimation as implemented in the *lme4* package (Bates et al., 2015). The

392 reported p-values were based on the t-distribution using degrees of freedom calculated with the  
393 Satterthwaites method, as implemented by the *lmerTest* package (Kuznetsova et al., 2017).

394 Differences between groups in object recognition performance were evaluated with a  
395 generalized linear model using a binomial distribution and a logit link function, as implemented in  
396 the R *stats* package. The same procedure was employed to evaluate the association between visual  
397 acuity and the AUC values in CC participants. All models' detailed specifications and output  
398 summaries are described in the corresponding figures' Extended data.

399

#### 400 **Open data and code accessibility**

401 The code for the statistical analyses, figures, and the anonymized, pre-processed data are  
402 available at the Research Data Repository of the University of Hamburg  
403 (DOI:10.25592/uhhfdm.1520). Original eye-tracking datasets are available upon request from the  
404 corresponding author.

405

406 **RESULTS**407 **Gaze stability is severely affected in CC participants**

408 As expected from the prevailing sensory nystagmus, eye movement trajectories were considerably  
409 altered in the CC group. **Fig. 1a** displays examples of a single trial eye-tracking recording from  
410 one participant of each group (see Video 1 and Video 2 and Extended data Fig. 1-1,1-2). SC and  
411 DC participants showed the prototypical gaze kinematics of visual exploration of static images:  
412 their gaze movements were characterized by periods of high stability (i.e. fixations) interrupted by  
413 short periods of displacement at a high velocity (i.e. saccades). By contrast, CC and NC  
414 participants' gaze movements were in a continuous, periodic displacement, as is typical of  
415 nystagmus. Participants' gaze stability was quantified in terms of instantaneous gaze velocity, that  
416 is, how fast and in which direction the eyes moved from one moment to another (see *Data*  
417 *analysis and statistics* – Instantaneous gaze velocity). The magnitude of instantaneous gaze  
418 velocity was significantly higher in CC as compared to SC individuals (robust linear model  
419 contrast,  $p < 0.001$ , see **Fig. 1b** and Extended data Fig. 1-3 for the full statistic results) and DC  
420 individuals ( $p < 0.001$ ), but lower than in NC individuals ( $p = 0.004$ ). Gaze velocities showed no  
421 clear direction in CC individuals, whereas for NC individuals, gaze velocities were mostly along  
422 the horizontal direction (see **Fig. 1c**). Such a pattern in NC individuals is typical of horizontal jerk  
423 nystagmus (Abadi and Bjerre, 2002).

424 In sum, these results confirm that in contrast to SC and DC participants, the gazes of CC  
425 and NC participants were in a state of continuous motion, that is, gaze stability was reduced in  
426 these two groups.

427

428

429

430 **Visual exploration patterns of CC participants are stimulus-driven and similar to those of**  
431 **controls**

432 Four examples of group-pooled exploration patterns overlaid over line drawings of the original  
433 grayscale images are depicted in **Fig. 2**. These images illustrate the resemblance of visual  
434 exploration patterns across groups. To quantitatively evaluate whether visual exploration patterns  
435 for natural scenes were stimulus-driven in CC participants and to what degree they followed the  
436 same principles as in normally sighted controls, informational entropy was derived to parametrize  
437 the width of the spatial distribution of gazed locations (Shiferaw et al., 2019). Low entropy scores  
438 indicate a low degree of randomness of visual exploration patterns (see *Data analysis and*  
439 *statistics – Entropy*).

440 As expected from the nystagmus-related gaze instability, visual exploration by CC  
441 individuals covered a wider area of the images than visual exploration by SC individuals. CC  
442 participants' entropy values were higher than for SC and DC participants (robust linear model  
443 contrasts, both  $p < 0.001$ , see **Fig. 3a** and Extended data Fig. 3-1 for statistics), but not different  
444 from those of the NC participants ( $p = 0.27$ ). Thus, higher entropy values in the CC group were a  
445 consequence of nystagmus, rather than of congenital visual deprivation.

446 Importantly, the CC group's entropy values for individual images were significantly  
447 correlated with entropy values of the same images for the three control groups (Pearson's  $r$ , all  $>$   
448  $0.5$  with  $p < 0.003$ , see **Fig. 3b**). Thus, the *relative* extent of visual exploration of images was  
449 correlated across groups. This correlation suggests that visual exploration by CC individuals was  
450 strongly dependent on the characteristics of the images, and that this dependency was  
451 qualitatively similar to the dependency on image characteristics which guided visual exploration  
452 in control individuals.

453 Since stimulus entropy assesses the extent of visual exploration, but not the precise  
454 locations of gaze shifts, similar entropy values across groups do not unambiguously indicate the

455 same visual exploration patterns. Therefore, we additionally evaluated whether the exploration  
456 patterns of the CC group were predicted by the corresponding visual exploration patterns of the  
457 SC group. For each image and participant, we used the pooled spatial distribution of gaze  
458 locations from the SC group to create an SC predictor map. We then used the latter to predict  
459 whether or not an image location was visually explored by CC individuals. Classification success  
460 was quantified by the area under the receiver operator characteristic curve (AUC; values larger  
461 than 0.5 indicate correct prediction, see *Data analysis and statistics – AUC*) (Swets, 1988;  
462 Fawcett, 2006).

463 SC predictor maps discriminated the CC group's gazed vs not-gazed locations above  
464 chance (all groups AUC values  $> 0.5$ , one-sample  $t$ -tests,  $p < 0.001$ , see **Fig. 3c**). In order to  
465 exclude the possibility that common image characteristics or spatial biases artificially enhanced  
466 prediction success, we ran a control analysis in which images were shuffled and AUC values from  
467 arbitrarily assigned images were derived. No successful prediction was achieved with these values  
468 (none of the AUC values in either group differed from 0.5,  $p > 0.05$ ). Although CC participants'  
469 AUC values were overall lower than those for SC and DC participants (robust linear model  
470 contrasts, both contrasts  $p < 0.001$ , see Extended data Fig. 3-2 for statistics), they did not differ  
471 from those of the NC participants ( $p = 0.93$ ).

472 In the CC group, AUC values were not correlated with visual acuity (Pearson's  $r_{(8)} = -$   
473  $0.19$ ,  $p = 0.59$ , see Extended data Figure 3-3), age at testing ( $r_{(8)} = -0.05$ ,  $p = 0.87$ ), age at cataract  
474 surgery ( $r_{(8)} = -0.28$ ,  $p = 0.42$ ) or time since sight restoration ( $r_{(8)} = 0.2$ ,  $p = 0.56$ ).

475 The previous analyses were based on the complete duration of a trial (4 s). To evaluate  
476 possible group differences in the temporal dynamics of visual exploration, we additionally ran the  
477 same analyses for the SC predictor maps separately for consecutive, non-overlapping 500 ms time  
478 intervals. For the first interval (0 to 500 ms after image presentation), all groups had low AUC  
479 values (AUC values around 0.5, see **Fig. 3d**). This result is consistent with previous findings and

480 is most likely due to the starting position being forced to be at the center of the image and thus  
481 independent of image content (Schütt et al., 2019). After the first interval, CC participants' AUC  
482 values increased, and remained at the same level throughout image presentation. By contrast, SC,  
483 DC and NC participants reached their highest AUC values in the second interval (500 to 1000  
484 ms), following which AUC values that progressively decreased until the end of image  
485 presentation. This group difference in the dynamics of visual exploration was confirmed by a  
486 mixed-effects model with a categorical predictor participant group, a time interval covariate  
487 (excluding the first interval), and participant identity as random effect: CC participants' estimate  
488 of a time interval covariate was not different from 0 ( $p = 0.9$ , see Extended data Fig. 3-4 for  
489 statistics). In other words, there was no relationship between time interval and AUC values in the  
490 CC group. By contrast, all the other groups showed a significantly more negative estimate of the  
491 time interval covariate than CC participants (all contrasts  $p < 0.006$ ), indicating a decrease of  
492 AUC values as exploration progressed in the control groups.

493 Previous research suggested that visual acuity depends on the extent of the stable,  
494 "foveation", period of the nystagmus (Dell'Osso and Daroff, 1975; Dell'Osso and Jacobs, 2002;  
495 Felius et al., 2011). Therefore, it is possible that CC and NC participants mainly explore the  
496 image during low-velocity periods of their nystagmus. To test this hypothesis in CC and NC  
497 participants, AUC values were separately calculated for ten data partitions according to the  
498 magnitude of the gaze instantaneous velocity (see **Fig. 3e**). AUC values were above chance for  
499 each velocity bin. A mixed-effects model with the categorical predictor group (run only with CC  
500 and NC groups), a velocity quantile covariate, and participant identity as random effect, revealed  
501 a significant effect of speed quantile ( $p = 0.002$ , see Extended data Fig. 3-5 for statistics), without  
502 a significant main effect of group ( $p = 0.6$ ) and without a significant interaction of group and the  
503 velocity quantile covariate ( $p = 0.83$ ). Therefore, across both groups, slower gaze velocities  
504 resulted in higher AUC values. The first two gaze velocity quantiles of CC and NC individuals



505 were roughly comparable to SC and DC individuals' instantaneous gaze velocity during fixations  
506 (see Extended data Fig. 3-6). This result suggests that CC and NC individuals were able to  
507 systematically adjust visual exploration in order to gaze at the most relevant parts of an image  
508 during the low-speed phase of the nystagmus, when visual discrimination seemed to be best in  
509 individuals with nystagmus.

510 Entropy and AUC values were correlated in all groups, demonstrating that the lower the  
511 spread of visual exploration, the higher the agreement of visual exploration patterns across  
512 participants (see **Fig. 3f** for the results of the CC group and Extended data Figure 3-7 for the  
513 corresponding results of the other groups). This correlation did not differ between any of the four  
514 groups (comparison of Fischer's Z-transformed  $r$  values, all  $p > 0.05$ ).

515 In summary, CC individuals gazed at similar locations of the image as normally sighted  
516 controls. These results support the hypothesis that the CC individuals' visual exploration was  
517 based on the same underlying mechanisms. Thus, neither the acquisition of these representations,  
518 nor their use for visual exploration via eye movements, seem to require patterned vision at birth.

519

### 520 **Exploration patterns of CC participants are guided by both low-level and high-level visual** 521 **features**

522 Next, we evaluated to what degree visual exploration patterns were guided by low-level versus  
523 high-level visual information. For this purpose, predictor maps from two different saliency  
524 models were computed for each image: A first, low-level predictor map was constructed from  
525 local contrast as defined by the Intensity Contrast Feature model (ICF) (Kümmerer et al., 2017).  
526 The second, high-level predictor map was constructed from features resulting from a deep neural  
527 network trained for object recognition, as defined by the DeepGaze II model (DG-II) (Kümmerer  
528 et al., 2016, 2017; Schütt et al., 2019).

529 In all groups, visual exploration patterns were classified above chance by both the low-  
530 level ICF and high-level DG-II predictor maps (see **Fig. 4 a,b**, all  $AUC > 0.5$ ,  $p < 0.001$ ). The  
531 high-level DG-II model predicted the visual exploration patterns better (i.e., resulted in higher  
532 AUC values) than the low-level ICF model for all groups (paired t-test: CC group :  $p = 0.01$ ; SC  
533 group:  $p < 0.001$ ; DC group:  $p < 0.001$ ) except for the NC group ( $p = 0.13$ ). We confirmed that  
534 this classification accuracy was not an artifact of general image characteristics or spatial biases:  
535 neither of the two models significantly predicted gaze patterns in either group after images were  
536 shuffled. These results suggest that CC individuals were able to make use of both low-level and  
537 high-level visual information for guiding visual exploration, similar to SC individuals.

538 AUC values were overall lower in the CC group compared to the SC and DC group for  
539 both low- and high-level predictor maps (robust linear model contrasts, all  $p < 0.004$ , see **Fig. 4**  
540 **a,b** and Extended data Fig. 4-1 and 4-2 for statistics), while they did not significantly differ from  
541 the corresponding AUC values of the NC group (both  $p > 0.05$ ). Importantly, the relative  
542 predictive power of the two models (ratio of the ICF and DG-II AUC values) was  
543 indistinguishable between the CC group and the three control groups (all  $p > 0.05$ , see **Fig. 4c** and  
544 Extended data Fig. 4-3 for statistics). This confirmed that CC individuals weighted low- and high-  
545 level visual information for guiding visual exploration similar to the SC, NC and DC groups.

546 As in the analysis for the SC predictor map, we ran the analyses for the ICF and DG-II  
547 predictor maps separately for consecutive time intervals (see Extended data Fig. 4-4). For the  
548 low-level ICF predictor, the time interval covariate was not significant in any group (estimate not  
549 different from 0, all  $p > 0.1$ , see Extended data Fig. 4-5 for statistics). For the high-level DG-II  
550 predictor, the SC group showed an effect of interval ( $p < 0.001$ ). By contrast, this effect was non-  
551 significant in the CC ( $p = 0.29$ ), DC ( $p = 0.06$ ) or NC ( $p = 0.12$ ) groups. Nevertheless, the  
552 estimate of the time interval covariate was more negative in the SC and DG group than in the CC  
553 group ( $p < 0.0002$  and  $p < 0.04$  respectively, see Extended data Fig. 4-6 for statistics).

554 Additionally, AUC values obtained from saliency predictor maps computed from low-pass  
555 filtered images explained visual exploration in the CC and NC groups better than in the SC and  
556 DC groups (see Extended data Figure 4-7, and 4-8 and 4-9 for statistics). This is consistent with  
557 CC and NC individuals' reduced visual acuity and reduced sensitivity to higher spatial  
558 frequencies (Elleberg et al., 1999; Bedell, 2006; Hertle and Reese, 2007). Thus, it is justified to  
559 conclude that CC and NC individuals' visual exploration predominantly made use of the low  
560 rather than high spatial frequency components of visual stimulus features.

561 In sum, these results demonstrate a highly preserved ability of CC individuals to use both  
562 low-and high-level visual information to guide visual exploration.

563

#### 564 **Changes in visual exploration patterns for repeated images indicate visual short-term** 565 **memory effects in CC individuals**

566 Visual exploration patterns narrow down after an image has been repeatedly encountered (Noton  
567 and Stark, 1971; Ryan et al., 2000; Smith et al., 2006; Kaspar and König, 2011). This result has  
568 been taken as evidence for visual exploration being guided not only by stimulus-driven but  
569 additionally by top-down factors. In order to assess such short-term memory effects, we analyzed  
570 differences in gaze entropy for two consecutive images, for which the second image was either (1)  
571 identical to the first image, (2) a different image but displaying an item of the same category as  
572 the first image or (3) a different, unrelated image.

573 Entropy values decreased between the first and second presentation of the same image in  
574 all groups, including the CC group (see **Fig. 5a**). Furthermore, this reduction in the spread of  
575 visual exploration between repeated images did not differ between groups (no significant  
576 interaction between image repetition and group,  $p > 0.05$ , see Extended data Fig. 5-1 for  
577 statistics). Importantly, in all groups, the reduction in entropy for consecutive images was specific

578 for repeated images and did not generalize to category repetitions or different images (see **Fig. 5a**  
579 and Extended data Figure 5-2,3 for statistics).

580 In summary, CC individuals' visual exploration patterns showed the same short-term  
581 memory related reduction in spread as found in the control groups and demonstrated in previous  
582 research (Noton and Stark, 1971; Ryan et al., 2000; Smith et al., 2006; Kaspar and König, 2011).  
583 This result suggests that CC individuals are able to integrate both stimulus-driven and top-down  
584 information from short-term memory, in order to guide visual exploration.

585

#### 586 **Object recognition performance is linked to systematic visual exploration in CC individuals**

587 Object recognition performance was high in all groups (see **Fig. 5b**). All SC participants,  
588 independent of their chronological age at testing, performed at 100%. Overall, the performance of  
589 the CC group (mean: 84,2% correct, range 30.3-100%) was lower than in the three other groups  
590 ( $p < 0.001$ ; see Extended data Fig. 5-4 for statistics). For CC participants, a logistic regression  
591 model analysis revealed that object recognition performance was associated with better visual  
592 acuity (visual acuity predictor,  $p < 0.001$ , see **Fig 5c** and Extended data Fig. 5-5 for statistics) but  
593 not with age at testing (see Extended data Figure 5-6,7). Crucially, object recognition was  
594 additionally related to how well the CC individuals' exploration patterns were predicted by the  
595 exploration patterns of SC participants (AUC predictor,  $p < 0.001$ ). According to AIC and Tjur  $R^2$   
596 model-fit metrics (see Extended data Fig. 5-5), a model with both the visual acuity and AUC  
597 predictors performed better at explaining the object recognition scores of CC individuals than a  
598 model with either predictor in isolation. While high overall object recognition performance in CC  
599 individuals is in accordance with previous findings (Ostrovsky et al., 2009; Röder et al., 2013),  
600 this result further suggests that object recognition performance in CC individuals might benefit  
601 from systematic visual exploration.

602

603 **DISCUSSION**

604 Visual exploration of natural scenes by means of eye movements is guided by stimulus-driven  
605 mechanisms that make use of low- and high-level visual features as well as by top-down  
606 mechanisms such as explicit goals and memory representations. The present study investigated  
607 the degree to which the development of the bottom-up and top-down mechanisms guiding  
608 systematic visual exploration of natural stimuli relies on early visual experience. Here, we tested  
609 visual exploration patterns in 10 individuals who had received delayed treatment for total dense  
610 bilateral congenital cataracts (CC group), some of whom only in late childhood or adulthood.  
611 Participants watched close-up photographic images of different objects, plants, animals and  
612 buildings. The visual exploration patterns of CC individuals were compared to those of a group of  
613 normally sighted controls (SC group), individuals treated for late-onset cataracts (DC group), and  
614 a group of individuals with pathological nystagmus, but without a history of congenital cataracts  
615 or visual deprivation (NC group). We found remarkably preserved visual exploration behavior in  
616 the CC group, despite an absence of visual experience early in life. Indeed, CC individuals' visual  
617 exploration patterns were successfully predicted by those of the SC group. The application of  
618 modelling approaches to identify the visual features guiding visual exploration revealed that CC  
619 individuals employed both low-level and high-level visual information, and did so with a similar  
620 relative weighting as observed in the control groups. Furthermore, by analyzing the effects of  
621 short-term memory on visual exploration patterns, we demonstrated that CC individuals were able  
622 to integrate recently acquired memory representations with stimulus-driven visual information.  
623 Finally, despite the high object recognition scores of CC individuals, residual deficits were  
624 associated not only with their persistent lower visual acuity, but additionally were associated with  
625 the degree to which their visual exploration patterns resembled those of typically sighted  
626 individuals.

627           While most studies in sight-recovery individuals have focused on visual perceptual  
628 functions, the interaction of the visual and oculomotor system has hardly ever been investigated in  
629 this population. On one hand, this is surprising, given that visual perception crucially depends on  
630 overt exploration to align the gaze with the most relevant regions of the visual world. On the other  
631 hand, eye movements of sight-recovery individuals born with severe visual impairment or  
632 blindness are highly distorted due to a superimposing involuntary nystagmus, making them harder  
633 to assess (Abadi et al., 2006). The emergence of nystagmus in CC individuals is a direct  
634 consequence of visual deprivation within the first 8-12 weeks of life; the first 12 weeks of life are  
635 considered a sensitive period for the development of gaze stability control (Rogers et al., 1981;  
636 Gelbart et al., 1982; Lambert et al., 2006; Birch et al., 2009). We observed more irregular  
637 nystagmus in CC individuals than in NC individuals, whose nystagmus patterns of horizontal jerk  
638 movements with accelerating slow phases were characteristic of Infantile Nystagmus syndrome.  
639 While Abadi et al. (2006) did not directly demonstrate such irregularities in the nystagmus pattern  
640 of CC individuals, their study reported that, in accordance with our observations, more irregular  
641 nystagmus, that is, with multiplanar rather than uniplanar patterns, seems to emerge in severe  
642 cases of congenital cataracts.

643           To the best of our knowledge, the present study is the first demonstration that individuals  
644 with nystagmus, regardless of etiology, are able to systematically explore natural images despite  
645 nystagmus related distortions. Previous research suggested that visual acuity in individuals with  
646 nystagmus depends on the duration of the “foveation” periods within their nystagmus (Dell’Osso  
647 and Daroff, 1975; Dell’Osso and Jacobs, 2002; Feliuss et al., 2011). In both the CC and NC  
648 groups, we observed that exploration was more predictable during low-velocity periods, that is  
649 during periods which by and large resemble foveation periods. Thus, individuals with nystagmus  
650 are capable of taking into account their idiosyncratic nystagmus pattern while exploring an image.  
651 However, it needs to be stressed that visual exploration was predictable in both the CC and the

652 NC groups for the complete range of gaze velocities. This result is in agreement with more recent  
653 research on visual acuity during nystagmus, which indicated that visual perception is possible  
654 throughout the nystagmus cycle (Dunn et al., 2014).

655         While a qualitative assessment of simple ocular orienting to light is routinely performed in  
656 CC individuals during clinical examination, the presence of nystagmus has made it difficult to  
657 quantitatively study systematic eye movement behavior in this group. It was only recently that  
658 visually guided behavior was successfully assessed with eye tracking in CC individuals (Zerr et  
659 al., 2020). In this study, participants followed a salient, single, visual target which abruptly but  
660 regularly changed location. CC individuals showed intact visually guided eye movements, which  
661 were as precise and as fast as can be expected after taking their nystagmus into account. While  
662 such visually guided eye movements are likely a prerequisite for the exploration of natural scenes,  
663 they might be accounted for, to a large degree, by a simple reflexive mechanism based on  
664 luminance contrast. By contrast, real-world visual exploration is not just driven by low-level  
665 information such as luminance contrast, but additionally uses high-level features, and integrates  
666 top-down influences such as goals and prior knowledge retrieved from memory (Tatler et al.,  
667 2011; König et al., 2016; Veale et al., 2017). Since previous research has documented better  
668 recovery of low-level than high-level visual processing in CC individuals (McKyton et al., 2015;  
669 Sourav et al., 2020; Pitchaimuthu et al., 2021), we expected that visual exploration of natural  
670 images would be mostly guided by low-level visual features. Contrary to this hypothesis, CC  
671 individuals relied on high-level information, and used both low- and high-level information in a  
672 similar manner to SC and DC control groups.

673         For all three predictor maps (SC group predictor maps, ICF and DG-II predictors), the  
674 AUC values were significantly higher than chance in predicting the gaze patterns of CC  
675 individuals. However, they were overall lower than what has often been reported in similar  
676 studies (Wilming et al., 2011; Bylinskii et al., 2016; Kümmerer et al., 2017). This might be due to



677 the characteristics of the images and constraints of the present study. First, all images featured a  
678 single central object, which might have reinforced a visual exploration bias towards the center.  
679 Since our analysis procedure controlled for this potential central bias, it might have lowered AUC  
680 values in the present study. Second, grayscale images were presented, which attenuated features  
681 that strongly guide typical visual exploration (Onat et al., 2014). Third, our analysis was not based  
682 only on fixations, but rather considered all eye-tracking gaze samples of the complete trial,  
683 including saccades. This was necessary due to the prevailing nystagmus in the CC and NC  
684 groups, and for a uniformity of the analysis across groups. By contrast, almost all previous studies  
685 that evaluate free-viewing behavior are based on fixations excluding saccades, and often  
686 excluding the first fixation following image presentation.

687         Although we found overall broader and less well-predicted visual exploration patterns in  
688 the CC group than in the SC and DC group, CC participants' visual exploration was overall  
689 comparable to visual exploration in the NC group. A difference between the CC and NC groups  
690 was however detected in a time interval resolved analysis: Whereas in SC, DC, and NC  
691 participants exploration was more predictable at the beginning of visual exploration (500 to 1000  
692 ms interval) than during later phases, CC participants showed consistent AUC values throughout  
693 the exploration period. Decreasing predictability of visual exploration has been observed in  
694 previous research (Onat et al., 2014; Schütt et al., 2019). This has been interpreted as an initial  
695 bottom-up orienting response, followed by a gradual broadening of visual exploration (Schütt et  
696 al., 2019). The initial strong bottom-up response has been shown to be a consequence of the use  
697 of high-level, rather than primary low-level features (Onat et al., 2014; Schütt et al., 2019).  
698 Indeed, this is the pattern of visual exploration that was observed in the SC group. In contrast to  
699 the SC group, prediction accuracy driven by high-level features did not vary with time in the CC  
700 individual. Thus, we speculate that despite using high level features for visual guidance, high-  
701 level information did not interact with the initial phase of bottom-up exploration in the CC group.



702 Future research might confirm this observation, since the dynamic change of predictability of the  
703 high-level model was not significant in the DC and NC groups.

704 It is unclear to which degree CC individuals are capable of visually exploring more  
705 complex scenes, e.g. images with multiple items, or images which are generally harder to perceive  
706 for them. In fact, as a recent study has reported that CC individuals conduct fewer eye movements  
707 to the eyes region (Zohary et al., 2022). In the present study we also avoided high stimulus  
708 eccentricities due to well-known deficits in peripheral vision of CC individuals (Lewis and  
709 Maurer, 2005), which is likely enhanced by the effects of nystagmus (Chung and Bedell, 1995;  
710 Pascal and Abadi, 1995) .

711 Stimulus-driven guidance of visual exploration is thought to emerge from topographical  
712 “feature maps” representing visual features such as color, orientation, luminance, and motion (Itti  
713 and Koch, 2001; Veale et al., 2017). It is assumed that these feature maps serve as a source for  
714 “saliency maps.” Saliency maps represent how conspicuous or “salient” different regions of the  
715 visual field might be (Koch and Ullman, 1985; Itti and Koch, 2000). Our results indicated that the  
716 emergence of both of these mechanisms - the extraction of visual feature maps as well as the  
717 computation of saliency maps - do not seem to depend on early visual experience during a  
718 sensitive period.

719 The computation of feature and saliency maps has been proposed to be followed by the  
720 derivation of a “priority map” (Bisley and Goldberg, 2010). Priority maps are thought to combine  
721 bottom-up stimulus-driven information and top-down constraints, in order to select the next gaze  
722 location (Bisley and Goldberg, 2010; Veale et al., 2017). Top down influences have often been  
723 studied by manipulating task instructions. A special case of a non-reflexive, implicit top-down  
724 influence on visual exploration is the effect of short-term memory: If an image is repeated, the  
725 distribution of gazed locations narrows down (Hannula, 2010). Short-term memory effects on  
726 visual exploration due to image repetition have been reported to be unrelated to changes in low-

727 level visual features (Kaspar and König, 2011), suggesting that these effects are neither due to  
728 low-level adaptation, nor due to a reweighting of low- and high-level image features. Whether or  
729 not the CC group would show memory-based gains on visual exploration over longer delay  
730 periods, as used in previous studies (Hannula, 2010), or other task based top-down effects, might  
731 be investigated in future studies.

732 CC participants were able to recognize the visual stimuli, in agreement with previous  
733 reports showing that even after a long period of congenital blindness, sight-recovery individuals  
734 were able to correctly name everyday objects (Maurer et al., 2005; Ostrovsky et al., 2009; Röder  
735 et al., 2013) and to recognize artificial objects through temporal integration (Orlov et al., 2021).  
736 In contrast to normally sighted participants who performed at ceiling, the CC group's  
737 performance on object recognition was not perfect in the present study. Crucially, better image  
738 recognition in CC individuals was associated not only with better visual acuity, but additionally  
739 with how much CC participants' gaze patterns resembled those of normally sighted controls.  
740 Although this association must be considered preliminary due to the limited sample size in the  
741 present study, this finding is compatible with previous research. For ambiguous or noisy stimuli,  
742 visual exploration of diagnostic features precedes explicit recognition, rather than object  
743 recognition guiding exploration (Holm et al., 2008; Kietzmann et al., 2011). The currently  
744 available data do not allow us to draw conclusions about whether object recognition is as fast in  
745 CC individuals as in controls. However, similar latencies of the N170 wave of event-related  
746 potentials, an electrophysiological component which has been associated with the structural  
747 encoding of objects, speaks in favor for a recovery of typical object recognition times in CC  
748 individuals (Röder et al., 2013). Since the overall low visual acuity in CC individuals can be  
749 considered analogous to noise, we speculate that visual exploration aided rather than interfered  
750 with object recognition in CC individuals.

751           The idea that visual exploration promotes object recognition is reminiscent of theories  
752 from developmental psychology on how infants learn to recognize objects. For example,  
753 information processing accounts assume that object recognition emerges in an active interaction  
754 with the visual world (Johnson and Johnson, 2000; Johnson, 2001; Johnson et al., 2008). Object  
755 recognition advances with an improvement in active sampling, that is, in visual exploration. It has  
756 been hypothesized that newborns' preference for edges and motion, as well as their ability for  
757 figure-ground segregation, acts as an initial guide for where to look (Slater et al., 1990; Johnson  
758 and Johnson, 2000; Johnson, 2001). Further, it was proposed that object-defining higher-level  
759 features are acquired while continuously exploring the visual world (Johnson and Johnson, 2000).  
760 For example, the level of object knowledge in 2-3.5 month old infants (Johnson et al., 2004) and  
761 the ability to process facial expressions in 6-11 month old infants (Amso et al., 2010) were found  
762 to depend on visual exploration patterns. Our results are consistent with the idea of active visual  
763 exploration being instrumental for the acquisition of object knowledge. We speculate that CC  
764 individuals' post-surgery visual exploration might initially have made use of the same preferences  
765 for edges and motion as suggested for newborns (Johnson and Johnson, 2000; Johnson, 2001).  
766 This additionally requires functioning oculomotor control in CC individuals, capable of taking  
767 nystagmus related trajectories into account. As children refine visual exploration to rely more on  
768 high-level features (Açık et al., 2010; Helo et al., 2014), we assume the same for CC individuals  
769 following cataract removal surgery. Indeed, CC individuals of the present study who had acquired  
770 the most typical visual exploration patterns were those who performed the best at object  
771 recognition.

772           None of the measures tested (i.e., entropy, AUC, and performance) showed an association  
773 with age at testing or time since surgery in CC participants. At first glance, this result seems  
774 surprising given the large range of ages at testing and of time passed since surgery. However, the  
775 lack of such a significant association requires replication, since our sample size was limited by the

776 availability of a rare population. Further, all CC participants were older than 10 years of age.  
777 Previous research has reported adult like visual exploration in terms of entropy and AUC  
778 measures in children older than 7 years of age (Açık et al., 2010; Helo et al., 2014). Finally, we  
779 tested CC individuals at least 7 months post-surgery. Thus, the duration since surgery within  
780 which visual input was available might have been sufficient to acquire visual exploration  
781 strategies, and the associated object knowledge. In fact, previous research in cataract-reversal  
782 individuals who underwent a long period of visual deprivation has provided evidence that  
783 knowledge of object shape emerges within this time period (Wright et al., 1992; Ostrovsky et al.,  
784 2009; Held et al., 2011; Chen et al., 2016).

785         In conclusion, the remarkably preserved exploration patterns of sight-recovery individuals  
786 with a history of a transient phase of congenital patterned visual deprivation suggests that the  
787 development of visual exploration mechanisms does not depend on experience within a sensitive  
788 period. In contrast to prevailing deficits in visual acuity, gaze stability, and other high-level visual  
789 functions (Röder and Kekunnaya, 2021b), visual exploration mechanisms seem to emerge after  
790 sight restoration. We speculate that similar to infants, the newly available, low spatial frequency  
791 information might initiate recovery in individuals with reversed congenital cataract; followed by  
792 refinement, as in typical ontogenetic development. Finally, it might be hypothesized that visual  
793 exploration after sight restoration surgery might stimulate the acquisition of visual object  
794 knowledge despite visual acuity deficits and nystagmus.

795

796 **REFERENCES**

797

798 Abadi RV, Bjerre A (2002) Motor and sensory characteristics of infantile nystagmus. *The British*  
799 *journal of ophthalmology* 86:1152–1160.

800 Abadi RV, Forster JE, Lloyd IC (2006) Ocular motor outcomes after bilateral and unilateral  
801 infantile cataracts. *Vision Research* 46:940–952.

802 Açık A, Onat S, Schumann F, Einhäuser W, König P (2009) Effects of luminance contrast and its  
803 modifications on fixation behavior during free viewing of images from different categories.  
804 *Vision research* 49:1541–1553.

805 Açık A, Sarwary A, Schultze-Kraft R, Onat S, König P (2010) Developmental changes in natural  
806 viewing behavior: Bottomup and top-down differences between children, young adults  
807 and older adults. *Frontiers in Psychology* 1:207.

808 Amso D, Fitzgerald M, Davidow J, Gilhooly T, Tottenham N (2010) Visual Exploration Strategies  
809 and the Development of Infants' Facial Emotion Discrimination. *Frontiers in Psychology*  
810 1:180.

811 Bahill AT, Kallman JS, Lieberman JE (1982) Frequency limitations of the two-point central  
812 difference differentiation algorithm. *Biol Cybern* 45:1–4.

813 Bamber D (1975) The area above the ordinal dominance graph and the area below the receiver  
814 operating characteristic graph. *Journal of Mathematical Psychology* 12:387–415.

815 Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using **lme4**.  
816 *Journal of Statistical Software* 67 Available at: <http://www.jstatsoft.org/v67/i01/>.

817 Bedell HE (2006) Visual and Perceptual Consequences of Congenital Nystagmus. *Seminars in*  
818 *Ophthalmology* 21:91–95.

819 Birch EE, Cheng C, Stager DR, Weakley DR, Stager DR (2009) The critical period for surgical  
820 treatment of dense congenital bilateral cataracts. *Journal of American Association for*  
821 *Pediatric Ophthalmology and Strabismus* 13:67–71.

822 Bisley JW, Goldberg ME (2010) Attention, intention, and priority in the parietal lobe. *Annual*  
823 *review of neuroscience* 33:1–21.

824 Brainard DH (1997) The psychophysics toolbox. *Spatial vision* 10:433–436.

825 Bylinskii Z, Judd T, Oliva A, Torralba A, Durand F (2016) What do different evaluation metrics tell  
826 us about saliency models? arXiv:160403605 [cs].

827 Chen J, Wu E-D, Chen X, Zhu L-H, Li X, Thorn F, Ostrovsky Y, Qu J (2016) Rapid Integration of  
828 Tactile and Visual Information by a Newly Sighted Child. *Current Biology* 26:1069–1074.

829 Chung STL, Bedell HE (1995) Effect of retinal image motion on visual acuity and contour  
830 interaction in congenital nystagmus. *Vision Research* 35:3071–3082.

831 Dell'Osso LF, Daroff RB (1975) Congenital nystagmus waveforms and foveation strategy.  
832 *Documenta Ophthalmologica* 39:155–182.

- 833 Dell'Osso LF, Jacobs JB (2002) An Expanded Nystagmus Acuity Function: Intra- and  
834 Intersubject Prediction of Best-Corrected Visual Acuity. *Documenta Ophthalmologica*  
835 104:28.
- 836 Dimigen O, Valsecchi M, Sommer W, Kliegl R (2009) Human microsaccade-related visual brain  
837 responses. *The Journal of Neuroscience* 29:12321–12331.
- 838 Dunn MJ, Margrain TH, Woodhouse JM, Ennis FA, Harris CM, Erichsen JT (2014) Grating visual  
839 acuity in infantile nystagmus in the absence of image motion. *Investigative*  
840 *Ophthalmology and Visual Science* 55:2682–2686.
- 841 Eckstein MP (2011) Visual search: A retrospective. *Journal of Vision* 11:14–14.
- 842 Einhäuser W, Martin KAC, König P (2004) Are switches in perception of the Necker cube related  
843 to eye position? *European Journal of Neuroscience* 20:2811–2818.
- 844 Einhäuser W, Rutishauser U, Koch C (2008a) Task-demands can immediately reverse the  
845 effects of sensory-driven saliency in complex visual stimuli. *Journal of vision* 8:2.1-19.
- 846 Einhäuser W, Spain M, Perona P (2008b) Objects predict fixations better than early saliency.  
847 *Journal of vision* 8:18.1-26.
- 848 Ellemberg D, Lewis TL, Maurer D, Hong Lui C, Brent HP (1999) Spatial and temporal vision in  
849 patients treated for bilateral congenital cataracts. *Vision Research* 39:3480–3489.
- 850 Engbert R (2003) Microsaccades uncover the orientation of covert attention. *Vision Research*  
851 43:1035–1045.
- 852 Fawcett T (2006) An introduction to ROC analysis. *Pattern Recognition Letters* 27:861–874.
- 853 Felius J, Fu VLN, Birch EE, Hertle RW, Jost RM, Subramanian V (2011) Quantifying Nystagmus  
854 in Infants and Young Children: Relation between Foveation and Visual Acuity Deficit.  
855 *Investigative Ophthalmology & Visual Science* 52:8724.
- 856 Ganesh S, Arora P, Sethi S, Gandhi TK, Kalia A, Chatterjee G, Sinha P (2014) Results of late  
857 surgical intervention in children with early-onset bilateral cataracts. *British Journal of*  
858 *Ophthalmology* 98:1424–1428.
- 859 Gelbart SS, Hoyt CS, Jastrebski G, Marg E (1982) Long-Term Visual Results in Bilateral  
860 Congenital Cataracts. *American Journal of Ophthalmology* 93:615–621.
- 861 Goldstein HP, Gottlob I, Fendick MG (1992) Visual remapping in infantile nystagmus. *Vision*  
862 *Research* 32:1115–1124.
- 863 Green DM, Swets JA (1988) *Signal Detection Theory and Psychophysics*. Peninsula Pub.
- 864 Hannula DE (2010) Worth a glance: using eye movements to investigate the cognitive  
865 neuroscience of memory. *Frontiers in Human Neuroscience* 4:166.
- 866 Held R, Ostrovsky Y, de Gelder B, Gandhi T, Ganesh S, Mathur U, Sinha P (2011) The newly  
867 sighted fail to match seen with felt. *Nat Neurosci* 14:551–553.
- 868 Helo A, Pannasch S, Sirri L, Rämä P (2014) The maturation of eye movement behavior: Scene  
869 viewing characteristics in children and adults. *Vision Research* 103:83–91.

- 870 Hensch TK (2005) Critical period plasticity in local cortical circuits. *Nature Reviews Neuroscience*  
871 6:877–888.
- 872 Hertle RW, Reese M (2007) Clinical contrast sensitivity testing in patients with infantile  
873 nystagmus syndrome compared with age-matched controls. *American journal of*  
874 *ophthalmology* 143:1063–1065.
- 875 Holland PW, Welsch RE (1977) Robust regression using iteratively reweighted least-squares.  
876 *Communications in Statistics - Theory and Methods* 6:813–827.
- 877 Holm L, Eriksson J, Andersson L (2008) Looking as if you know: Systematic object inspection  
878 precedes object recognition. *Journal of Vision* 8:14.
- 879 Holmqvist K, Nyström M, Andersson R, Dewhurst R, Jarodzka H, van de Weijer J (2011) *Eye*  
880 *Tracking: A comprehensive guide to methods and measures*. OUP Oxford.
- 881 Itti L, Koch C (2000) A Saliency-Based Search Mechanism for Overt and Covert Shifts of Visual  
882 Attention. *Vision Research* 40:1489–1506.
- 883 Itti L, Koch C (2001) Computational modelling of visual attention. *Nature Reviews Neuroscience*  
884 2:194–203.
- 885 Jin YH, Goldstein HP, Reinecke RD (1989) Absence of visual sampling in infantile nystagmus.  
886 *Korean J Ophthalmol* 3:28–32.
- 887 Johnson SP (2001) Visual development in human infants: Binding features, surfaces, and  
888 objects. *Visual Cognition* 8:565–578.
- 889 Johnson SP, Davidow J, Hall-Haro C, Frank MC (2008) Development of perceptual completion  
890 originates in information acquisition. *Developmental Psychology* 44:1214–1224.
- 891 Johnson SP, Johnson KL (2000) Early perception-action coupling: eye movements and the  
892 development of object perception. *Infant Behavior and Development* 23:461–483.
- 893 Johnson SP, Slemmer JA, Amso D (2004) Where Infants Look Determines How They See: Eye  
894 Movements and Object Perception Performance in 3-Month-Olds. *Infancy* 6:185–201.
- 895 Kaspar K, König P (2011) Overt Attention and Context Factors: The Impact of Repeated  
896 Presentations, Image Type, and Individual Motivation. *PLoS ONE* 6:e21719.
- 897 Kaspar K, König P (2011) Viewing behavior and the impact of low-level image properties across  
898 repeated presentations of complex scenes. *Journal of Vision* 11:26–26.
- 899 Kienzle W, Franz MO, Schölkopf B, Wichmann F a (2009) Center-surround patterns emerge as  
900 optimal predictors for human saccade targets. *Journal of vision* 9:7.1-15.
- 901 Kietzmann TC, Geuter S, König P (2011) Overt Visual Attention as a Causal Factor of Perceptual  
902 Awareness. *PloS one* 6:e22614.
- 903 Kleiner M, Brainard D, Pelli D (2007) What's new in Psychtoolbox-3? Perception ECVF abstract  
904 36.
- 905 Knudsen EI (2004) Sensitive Periods in the Development of the Brain and Behavior. *Journal of*  
906 *Cognitive Neuroscience* 16:1412–1425.



- 907 Koch C, Ullman S (1985) Shifts in selective visual attention: towards the underlying neural  
908 circuitry. *Human neurobiology* 4:219–227.
- 909 König P, Wilming N, Kietzmann TC, Ossandón JP, Onat S, Ehinger BV, Gameiro RR, Kaspar K  
910 (2016) Eye movements as a window to cognitive processes. *Journal of Eye Movement*  
911 *Research* 9:1–16.
- 912 Kümmerer M, Wallis TSA, Bethge M (2016) DeepGaze II: Reading fixations from deep features  
913 trained on object recognition. arXiv:161001563.
- 914 Kümmerer M, Wallis TSA, Gatys LA, Bethge M (2017) Understanding Low- and High-Level  
915 Contributions to Fixation Prediction. In: 2017 IEEE International Conference on Computer  
916 Vision (ICCV), pp 4799–4808. Venice: IEEE.
- 917 Kuznetsova A, Brockhoff PB, Christensen RHB (2017) **ImerTest** Package: Tests in Linear Mixed  
918 Effects Models. *Journal of Statistical Software* 82 Available at:  
919 <http://www.jstatsoft.org/v82/i13/>.
- 920 Lambert SR, Lynn MJ, Reeves R, Plager DA, Buckley EG, Wilson ME (2006) Is There a Latent  
921 Period for the Surgical Treatment of Children With Dense Bilateral Congenital Cataracts?  
922 *Journal of American Association for Pediatric Ophthalmology and Strabismus* 10:30–36.
- 923 Le Grand R, Mondloch CJ, Maurer D, Brent HP (2001) Early Visual Experience and Face  
924 Processing. *Nature* 412:26–27.
- 925 Lewis TL, Maurer D (2005) Multiple sensitive periods in human visual development: Evidence  
926 from visually deprived children. *Developmental Psychobiology* 46:163–183.
- 927 Maurer D, Lewis TL, Mondloch CJ (2005) Missing sights: Consequences for visual cognitive  
928 development. *Trends in Cognitive Sciences* 9:144–151.
- 929 Maurer D, Mondloch CJ, Lewis TL (2007) Sleeper effects. *Developmental Science* 10:40–47.
- 930 McKyton A, Ben-Zion I, Doron R, Zohary E (2015) The Limits of Shape Recognition following  
931 Late Emergence from Blindness. *Current Biology* 25:2373–2378.
- 932 Noton D, Stark L (1971) Scanpaths in Eye Movements during Pattern Perception. *Science*  
933 171:308–311.
- 934 Nuthmann A, Henderson JM (2010) Object-based attentional selection in scene viewing. *Journal*  
935 *of vision* 10:20.
- 936 Onat S, Açık A, Schumann F, König P (2014) The contributions of image content and behavioral  
937 relevancy to overt attention. *PLoS ONE* 9:e93254.
- 938 Orlov T, Raveh M, McKyton A, Ben-Zion I, Zohary E (2021) Learning to perceive shape from  
939 temporal integration following late emergence from blindness. *Current Biology* 31:3162-  
940 3167.e5.
- 941 Ostrovsky Y, Meyers E, Ganesh S, Mathur U, Sinha P (2009) Visual Parsing After Recovery  
942 From Blindness. *Psychological Science* 20:1484–1491.
- 943 Otero-Millan J, Castro JLA, Macknik SL, Martinez-Conde S (2014) Unsupervised clustering  
944 method to detect microsaccades. *Journal of Vision* 14:18–18.



- 945 Pascal E, Abadi RV (1995) Contour interaction in the presence of congenital nystagmus. *Vision*  
946 *research* 35:1785–1789.
- 947 Pitchaimuthu K, Dormal G, Sourav S, Shareef I, Rajendran SS, Ossandón JP, Kekunnaya R,  
948 Röder B (2021) Steady state evoked potentials indicate changes in nonlinear neural  
949 mechanisms of vision in sight recovery individuals. *Cortex* 144:15–28.
- 950 Putzar L, Hötting K, Röder B (2010) Early visual deprivation affects the development of face  
951 recognition and of audio-visual speech perception. *Restorative Neurology and*  
952 *Neuroscience* 28:251–257.
- 953 Putzar L, Hötting K, Rösler F, Röder B (2007) The development of visual feature binding  
954 processes after visual deprivation in early infancy. *Vision Research* 47:2616–2626.
- 955 Röder B, Kekunnaya R (2021a) Visual experience dependent plasticity in humans. *Curr Opin*  
956 *Neurobiol* 67:155–162.
- 957 Röder B, Kekunnaya R (2021b) Visual experience dependent plasticity in humans. *Current*  
958 *Opinion in Neurobiology* 67:155–162.
- 959 Röder B, Ley P, Shenoy BH, Kekunnaya R, Bottari D (2013) Sensitive periods for the functional  
960 specialization of the neural system for human face processing. *Proceedings of the*  
961 *National Academy of Sciences* 110:16760–16765.
- 962 Rogers GL, Tishler CL, Tsou BH, Hertle RW, Fellows RR (1981) Visual Acuities in Infants With  
963 Congenital Cataracts Operated on Prior to 6 Months of Age. *Archives of Ophthalmology*  
964 99:999–1003.
- 965 Rossion B, Torfs K, Jacques C, Liu-Shuang J (2015) Fast periodic presentation of natural  
966 images reveals a robust face-selective electrophysiological response in the human brain.  
967 *Journal of Vision* 15:18–18.
- 968 Ryan JD, Althoff RR, Whitlow S, Cohen NJ (2000) Amnesia is a Deficit in Relational Memory.  
969 *Psychological Science* 11:454–461.
- 970 Schulze-Bonsel K, Feltgen N, Burau H, Hansen L, Bach M (2006) Visual Acuities “Hand Motion”  
971 and “Counting Fingers” Can Be Quantified with the Freiburg Visual Acuity Test.  
972 *Investigative Ophthalmology & Visual Science* 47:1236.
- 973 Schütt HH, Rothkegel LOM, Trukenbrod HA, Engbert R, Wichmann FA (2019) Disentangling  
974 bottom-up versus top-down and low-level versus high-level influences on eye movements  
975 over time. *Journal of Vision* 19:1.
- 976 Shiferaw B, Downey L, Crewther D (2019) A review of gaze entropy as a measure of visual  
977 scanning efficiency. *Neuroscience & Biobehavioral Reviews* 96:353–366.
- 978 Simonyan K, Zisserman A (2014) Very Deep Convolutional Networks for Large-Scale Image  
979 Recognition. *arXiv:14091556 [cs]*.
- 980 Slater A, Morison V, Somers M, Mattock A, Brown E, Taylor D (1990) Newborn and older infants’  
981 perception of partly occluded objects. *Infant Behavior and Development* 13:33–49.
- 982 Smith CN, Hopkins RO, Squire LR (2006) Experience-Dependent Eye Movements, Awareness,  
983 and Hippocampus-Dependent Memory. *Journal of Neuroscience* 26:11304–11312.

- 984 Sourav S, Bottari D, Shareef I, Kekunnaya R, Röder B (2020) An electrophysiological biomarker  
985 for the classification of cataract-reversal patients: A case-control study. *EClinicalMedicine*  
986 27:100559.
- 987 SR Research (2019) Models of Velocity and Acceleration Calculations. In: Experiment Builder  
988 2.2.1 [Computer software]. Mississauga, Ontario, Canada: SR Research Ltd.
- 989 Stampe DM (1993) Heuristic filtering and reliable calibration methods for video-based pupil-  
990 tracking systems. *Behavior Research Methods, Instruments, & Computers* 25:137–142.
- 991 Swets JA (1988) Measuring the Accuracy of Diagnostic Systems. *Science* 240:1285–1293.
- 992 Tatler BW (2007) The central fixation bias in scene viewing: Selecting an optimal viewing  
993 position independently of motor biases and image feature distributions. *Journal of Vision*  
994 7:1–17.
- 995 Tatler BW, Baddeley R, Gilchrist I (2005) Visual correlates of fixation selection: effects of scale  
996 and time. *Vision research* 45:643–659.
- 997 Tatler BW, Hayhoe M, Land M, Ballard D (2011) Eye guidance in natural vision: Reinterpreting  
998 salience. *Journal of vision* 11:1–23.
- 999 Veale R, Hafed ZM, Yoshida M (2017) How is visual salience computed in the brain? Insights  
1000 from behaviour, neurobiology and modelling. *Philosophical Transactions of the Royal*  
1001 *Society B: Biological Sciences* 372:20160113.
- 1002 Waugh SJ, Bedell HE (1992) Sensitivity to Temporal Luminance Modulation in Congenital  
1003 Nystagmus. *Investigative Ophthalmology & Visual Science* 33:9.
- 1004 Wilming N, Betz T, Kietzmann TC, König P (2011) Measures and Limits of Models of Fixation  
1005 Selection. *PloS one* 6:e24038.
- 1006 World Health Organization (2019) Vision impairment. In: World report on vision (Gilbert C,  
1007 Jackson ML, Kyari F, Naidoo K, Rao GN, Resnikoff S, West S, eds), pp 10–16. World  
1008 Health Organization. Available at: <https://apps.who.int/iris/handle/10665/328717>.
- 1009 Wright KW, Christensen LE, Noguchi BA (1992) Results of Late Surgery for Presumed  
1010 Congenital Cataracts. *American Journal of Ophthalmology* 114:409–415.
- 1011 Zerr P, Ossandón JP, Shareef I, Van der Stigchel S, Kekunnaya R, Röder B (2020) Successful  
1012 visually guided eye movements following sight restoration after congenital cataracts.  
1013 *Journal of Vision* 20:3.
- 1014 Zohary E, Harari D, Ullman S, Ben-Zion I, Doron R, Attias S, Porat Y, Sklar AY, Mckyton A  
1015 (2022) Gaze following requires early visual experience. *Proc Natl Acad Sci USA*  
1016 119:e2117184119.
- 1017
- 1018

1019 **Video 1 and Video 2. Examples of visual exploration patterns.** Each subpanel shows the  
1020 exploration of one participant for the complete period of image presentation. Each red dot  
1021 represents one eye-tracking gaze sample (down sampled from 500 Hz to 125 Hz for better  
1022 visualization) overlaid on a line-drawing sketch of the original photographic grayscale image;  
1023 note that participants watched the original grayscale images.

1024

1025 **Figure 1. Eye movement kinematics during the visual exploration of an example image. (a)**  
1026 Examples of eye movement recordings of one participant from each group. Images were explored  
1027 for 4 seconds. The left panels depict the gaze traces overlaid on a line-drawing sketch of the  
1028 original photographic grayscale image; note that participants watched the original grayscale  
1029 images. The right panels show eye movement traces as they progress over time and space along  
1030 the horizontal (dark lines) and vertical (light lines) dimension. See Extended data Fig. 1-1 and 1-2  
1031 which show two other examples of eye movement recordings. **(b)** Distribution of the magnitude  
1032 of instantaneous gaze velocity. Light lines indicate each participant's distribution and dark lines  
1033 each group's average distribution. Colored circles display each participant's median value, and  
1034 the yellow dots and error bars display the group's mean and s.e.m. See Extended data Fig. 1-3 for  
1035 statistics. **(c)** Distribution of instantaneous gaze velocity (bin size = 16 °/s, densities were  
1036 individually generated for each participant and then averaged across the participants of each  
1037 group). The color scale indicates the probability of a given gaze velocity in  $\log_{10}$  scale. Yellow  
1038 and white contours indicate areas that span approximately 75% and 90% of the distribution. In all  
1039 figures, significant contrasts among groups are indicated with one, two or three "\*" corresponding  
1040 to p-values of  $< 0.01$ ,  $< 0.001$ , and  $< 0.0001$ , respectively. CC – congenital cataract group; SC –  
1041 normally sighted controls; DC – developmental cataract controls; NC – nystagmus controls.

1042

1043 **Figure 2. Examples of visual exploration by group.** The subpanels show, for different images  
1044 and the four groups of participants (see Figure 1 for description) the spatial distributions of the  
1045 probabilities to gaze different locations (pooled across participants and smoothed with a 2D  
1046 Gaussian unit kernel), superimposed over line-drawing sketches of the original images. Warmer  
1047 colors indicate higher probability to gaze a location. Yellow contours indicate areas that span the  
1048 top 50%, 75% and 95% of the spatial distribution. As this distribution are constructed from all  
1049 gaze eye-tracking samples (each occurring every 2 ms), these maps are equivalent to the spatial  
1050 distributions of dwell time. The mean of entropy and AUC values for each of the four images are  
1051 indicated by the corresponding symbol (star, square, and left and right pointing triangles) in Fig.  
1052 3b,d. The last column shows the DG-II and ICF predictor maps for each image. Extended data  
1053 Fig. 2-1 show the grand average of the spatial distributions of the probability to gaze a certain  
1054 location across all images separately for each of the four groups. In addition, the corresponding  
1055 grand average DG-II and ICF predictor maps are displayed.

1056

1057 **Figure 3. Spatial spread and predictability of visual exploration patterns.** (a) Mean gaze  
1058 entropy for each group (yellow dot with error bars, indicating the standard error of the mean) as  
1059 well as for individual participants (colored dots). See Extended data Fig. 3-1 for statistics. (b) CC  
1060 participants gaze entropy per image compared to the gaze entropy values of the other three control  
1061 groups. Colored continuous lines indicate a linear regression line for entropy values of the CC  
1062 group (x-axis) and each one of the three control groups (SC: blue; DC: green; NC: orange). The  
1063 top left inset depicts the corresponding Pearson's correlation values (in a red scale, upper right  
1064 corner) and the corresponding p-values (in green, lower left corner). Asterisks indicate significant  
1065 correlations after controlling for multiple comparisons ( $\alpha = 0.05/6$ ). (c) AUC values of the SC  
1066 predictor map per participant and group. Dark colored dots indicate AUC values for individual  
1067 participants as derived by the SC group's predictor maps to classify gaze and non-gazed location.

1068 Light colored circles from the corresponding AUC values for the control analysis in which image  
1069 correspondence was shuffled. Bottom colored stars indicate that actual and control analysis values  
1070 significantly differed. The control analysis values were not different from 0.5 (chance level). See  
1071 Extended data Fig. 3-2 for statistics and Extended data Fig. 3-3 for the relationship between AUC  
1072 values and different CC participants' characteristics. **(d)** AUC values of the SC predictor map  
1073 across time. Curves show, for each group, AUC values calculated from consecutive 500 ms data  
1074 partitions. See Extended data Fig. 3-4 for statistics. **(e)** AUC values of the SC predictor map as a  
1075 function of instantaneous gaze velocity. SC predictor maps were used to calculate gaze in CC  
1076 individuals separately for ten quantiles of instantaneous gaze velocity. See Extended data Fig. 3-5  
1077 for statistics. Extended data Fig. 3-6 show the relationship between gaze velocity during fixations  
1078 (SC and DC groups) and CC and NC participants' 1<sup>st</sup> and 2<sup>nd</sup> instantaneous gaze velocity  
1079 quantiles **(f)** Correlations of entropy and AUC values across all images for the CC group.  
1080 Different object categories are color coded. Extended data Figure 3-7 show the same correlation  
1081 for SC, NC, and DC groups.

1082

1083

1084 **Figure 4. Degree of explained visual exploration behavior for low- and high-level visual**  
1085 **information and context.** **(a)** AUC values resulting from the low-level ICF predictor maps. See  
1086 Extended Data Fig. 4-1 for statistics. **(b)** AUC values resulting from the high-level DG-II  
1087 predictor maps. See Extended Data Fig. 4-2 for statistics. **(c)** Ratio between ICF and DG-II AUC  
1088 values. See Extended Data Fig. 4-3 for statistics. Extended data Fig. 4.4-6 show AUC values of  
1089 the ICF and DG-II predictor map across time and the corresponding statistics. Extended data  
1090 Figure 4-7 shows the ratio between ICG and DG-II AUC values obtained from low-pass filtered  
1091 versions of the images and the AUC values obtained from the non-filtered images. See Extended  
1092 data Fig. 4-8 to 4-9 for statistics.

1093

1094 **Figure 5. Effect of stimulus repetition and object recognition performance.** (a) Gaze entropy  
1095 for the first vs. the second presentation of the same image (si), different images from the same  
1096 object category (soc), and different images from different object categories (doc). See Extended  
1097 data Fig. 5-1,2,3 for statistics. (b) Percentage correct images recognized for in each group (mean  
1098 group performance in black with error bars indicating the standard error of the mean). See  
1099 Extended data Fig. 5-4 for statistics (c) Recognition performance, visual acuity (logMar) and  
1100 AUC values (obtained using SC predictor maps) for each CC individual. The blue shade mesh  
1101 depicts the generalized logistic fit. Black lines starting at the red dots indicate the discrepancy  
1102 between actual performance of a CC participant and model predictions. See Extended data Fig. 5-  
1103 5 for statistics Extended data Figure 5-6,7 show the relationship between Performance vs. age at  
1104 testing.

1105

1106 **Extended data Table 1-1.** (a) Visual acuity (in decimal) vs. age of surgery for the CC and DC  
1107 individuals. (b) Visual acuity (in decimal) vs age at testing for all groups.

1108

1109 **Extended data Figure 1-1.** Examples of eye movement recordings of one participant from each  
1110 of the four groups.

1111 **Extended data Figure 1-2.** Examples of eye movement recordings of one participant from each  
1112 of the four groups.

1113 **Extended data Figure 1-3.** Instantaneous gaze velocity statistical result.

1114

1115 **Extended data Figure 2-1. Exploratory and feature bias.** (a) Grand average, across all image  
1116 and participants (per group), of the spatial distributions of the probability to gaze. (b) Grand  
1117 average, across all images, of DG-II and ICF predictor maps.

1118

1119 **Extended data Figure 3-1.** Entropy statistical result

1120 **Extended data Figure 3-2.** AUC (SC predictor map) statistical result

1121 **Extended data Figure 3-3.** Relationship between SC predictor map AUC values in CC  
1122 individuals and (a) logMAR visual acuity, (b) age at testing, (c) age at surgery, and (d) time from  
1123 surgery.

1124 **Extended data Figure 3-4.** AUC (SC predictor) per time interval statistical result

1125 **Extended data Figure 3-5.** AUC (SC predictor) per velocity quantile statistical result

1126 **Extended data Figure 3-6. Fixational gaze velocity SC and DC groups and 1<sup>st</sup> and 2<sup>nd</sup>**

1127 **quantiles of gaze velocity in the CC and NC groups.** Top panel show the grand average

1128 distribution, for the SC and DC groups, of the magnitude of instantaneous gaze velocity for

1129 samples corresponding to fixations. The lower panel show gaze instantaneous velocity first and

1130 second decile values for each CC and NC participant.



1131 **Extended data Figure 3-7. Correlation across images between entropy values and AUC**  
1132 **values. (a) SC, (b) NC, and (c) DC groups.**  
1133

1134 **Extended data Figure 4-1. AUC (ICF predictor map) statistical result**  
1135 **Extended data Figure 4-2. AUC (DG-II predictor map) statistical result**  
1136 **Extended data Figure 4-3. ICF/DG-II AUC ratio statistical result**  
1137 **Extended data Figure 4-4. AUC values across time. Curves show, for each group, AUC values**  
1138 **calculated from consecutive 500 ms data partitions. (a) ICF predictor. (B) DG-II predictor. See**  
1139 **Extended data Fig. 4-5 and 4-6 for statistics.**

1140 **Extended data Figure 4-5. AUC (ICF predictor) per time interval statistical result**  
1141 **Extended data Figure 4-6. AUC (DG-II predictor) per time interval statistical result**  
1142 **Extended data Figure 4-7. Ratio between AUC values for saliency predictor map obtained from**  
1143 **low-pass filtered versions of the images and the AUC values obtained from the non-filtered**  
1144 **images, for (a) the ICF and (b) DG-II predictor maps. ICF and DG-II saliency models were run**  
1145 **with low-pass filtered versions of the images using a 0.5, 1, and 2 visual degrees spatial frequency**  
1146 **cut-off. Group differences were evaluated separately per predictor map and filtered version with**  
1147 **robust linear model contrasts. The ratio between ICF predictor map AUC values from images**  
1148 **filtered at 0.5° and non-filtered images was higher in the CC group compared to the SC group**  
1149 **( $t_{(38)} = -2.82, p = 0.007$ , see Extended data Fig. 4-8 for statistics ) and the DC group ( $t_{(38)} = -3.51, p$**   
1150  **$= 0.001$ ), but not significant different from the NC group ( $t_{(38)} = -1.06, p = 0.29$ ). No difference**  
1151 **between groups was found for the 1° ratio or 2° ratio AUC. The ratio between DG-II predictor**  
1152 **map AUC values from images filtered at 0.5° and non-filtered images was higher in the CC and**  
1153 **NC groups compared to the SC and DC group (all four *contrast*,  $p < 0.007$ , see Extended data Fig.**  
1154 **4-9), but not different in the comparison between CC and NC ( $p = 0.79$ ). The ratio between AUC**  
1155 **values from images filtered at 1° and non-filtered images was higher in the CC compared to the**



1156 DC group ( $p = 0.005$ ). No other group contrast was significant. No group difference was found  
1157 for the DG-II 2°. In summary, compared to SC and DC participants for CC and NC participants  
1158 gazed- and non-gazed locations were to a larger degree predicted by the low spatial spectral  
1159 content of the images.

1160 **Extended data Figure 4-8.** AUC (ICF predictor map low pass 0.5 filtered) statistical result

1161 **Extended data Figure 4-9.** AUC (DG-II predictor map low pass 0.5 filtered) statistical result

1162

1163 **Extended data Figure 5-1.** Entropy values for the first vs. second image of a pair of identical

1164 images statistical result

1165 **Extended data Figure 5-2.** Entropy values for the first vs. second image of a pair of images from

1166 same category statistical result

1167 **Extended data Figure 5-3.** Entropy values for the first vs. second image of a pair of images from

1168 different category statistical result

1169 **Extended data Fig. 5-4.** Performance for each group statistical result

1170 **Extended data Fig. 5-5.** CC participants' performance statistical result.

1171 **Extended data Fig. 5-6.** Performance vs. age at testing. Age at testing was not correlated with  
1172 performance across all participants ( $r = 0.06$ ,  $p = .69$ ) nor when tested only for the CC group ( $r =$

1173  $.1$ ,  $p = .78$ ). For CC participants, a logistic regression model analysis showed no association

1174 between object recognition performance and age at testing ( $p = 0.17$ , see Extended data Fig. 5-7).

1175 **Extended data Fig. 5-7.** CC participants' performance and age statistical result.

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