

Color vision in sight recovery individuals

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2 Color vision in sight recovery individuals

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21 **Abstract**

22 Background: Color vision has been consistently shown to be unaffected in animals that are
23 raised in dark or in color-deprived environments. However, there are only a few studies that
24 directly addressed the effect of congenital visual deprivation in color perception in humans.

25 Objective: The goal of the current study was to assess the effect of congenital visual
26 deprivation on color vision using a panel based color arrangement test.

27 Methods: We investigated the recovery of color vision using the Farnsworth D15 test in a
28 group of individuals who had experienced visual deprivation since birth due to bilateral dense
29 congenital cataracts before undergoing cataract-reversal surgery (Congenital cataract, CC, n =
30 12). In addition, we tested two groups of control participants: (1) individuals who had had non-
31 dense congenital cataract or developed cataract later in their childhood (Developmental
32 cataract, DC, n = 10), and (2) sighted controls with normal or corrected to normal vision (n =
33 14). Based on the methods proposed by Vingrys and King-Smith (1988), we derived the
34 following metrics of color vision performance: (1) total error score, (2) confusion index, (3)
35 confusion angle, and (4) selectivity index.

36 Results: All of the measured indices of color vision performance were unaltered by a period of
37 congenital visual deprivation.

38 Conclusions: Our results support the view that, development of visual functions such as color
39 discrimination and color arrangement does not depend on typical visual experience during a
40 sensitive phase in early childhood.

41 **Keywords:**

42 Color vision, sensitive period, congenital cataract, visual deprivation, Farnsworth D15

43 Introduction

44 Visual input during the early periods after birth has been found to be crucial for the
45 development of various visual and multisensory functions. Even a transient period of absence
46 of vision was shown to cause some irreversible visual damage. For example, individuals who
47 did not experience any patterned visual input for a period of time after birth due to the
48 presence of bilateral dense congenital cataracts were shown to have deficits in visual acuity
49 (Elleberg, Lewis, Maurer, Lui, & Brent, 1999), stereo-acuity (Tytla, Lewis, Maurer, & Brent,
50 1993), face and object processing (Le Grand, Mondloch, Maurer, & Brent, 2001; Röder, Ley,
51 Shenoy, Kekunnaya, & Bottari, 2013), and global motion perception (Bottari et al., 2018;
52 Hadad, Maurer, & Lewis, 2012). However, there are other visual functions which were found
53 to be less affected by a transient period of congenital visual deprivation, including biological
54 motion processing (Bottari et al., 2015; Hadad et al., 2012) and the presence of a retinotopic
55 representation and processing in the visual cortex (Sourav, Bottari, Kekunnaya, & Röder,
56 2018).

57 Non-human animal studies have consistently shown that different aspects of color
58 processing, including wavelength discrimination, spectral sensitivity, and color-based object
59 categorization are not affected by dark or red-light rearing (Boothe, Teller, & Sackett, 1975;
60 Brenner, Cornelissen, & Nuboer, 1990; Brenner, Schelvis, & Nuboer, 1985; Petry & Kelly,
61 1991). Boothe et al. (1975) reported that an infant monkey raised in darkness from the age of
62 2 weeks to 3 months after birth was able to discriminate all of the tested wavelengths from
63 white light. Moreover, both in pigeons (Brenner, Spaan, Wortel, & Nuboer, 1983) and in
64 monkeys (Brenner et al., 1990, 1985), it has been shown that rearing in a color deprived
65 environment (such as red illumination) did not alter the ability to discriminate objects based

66 on colors and spectral sensitivity curves (Brenner et al., 1990, 1985). Furthermore, both
67 chromatic opponency (a retinal aspect of color vision) and chromatic induction (a cortical
68 aspect of color vision) (Livingstone & Hubel, 1984; Michael, 1978) were observed to be
69 unaffected in a red light reared macaque monkey (Brenner et al., 1990). Despite this
70 compelling evidence of normal color development in color deprived or visually deprived non-
71 human animals, there are only a few human studies that reported the effect of visual
72 deprivation on the development of color perception.

73 Maurer, Lewis, & Brent (1989) used the Hardy-Rand-Rittler (HRR) pseudoisochromatic
74 plates and reported normal color vision performance in children treated for bilateral
75 congenital cataract (n = 14 eyes of 9 children, diagnosed before 6 months of age, and optical
76 correction was given between 4.4 to 16.4 months) as well as bilateral developmental cataract
77 (n = 9 eyes from 5 children, diagnosed between 7 months to 66 months, and optically
78 corrected 2.5 to 29 months later). McKyton, Ben-Zion, Doron, & Zohary (2015) found that the
79 ability to identify an odd item that differed in its color content from an array similar items did
80 not differ between individuals with “early treated cataract” (n = 8, 7 individuals operated \leq 6
81 months of age, and one individual operated at 21 months of age) and sighted control
82 observers (n = 11) whose vision was blurred according to their age-matched cataract cases’
83 contrast sensitivity deficits. In addition, McKyton et al. (2015) included a group of “late treated
84 cataract” individuals (n = 11, operated between 5.6 – 9.9 years of age). Within this “late
85 treated cataract” group, individuals who were tested more than 1 year after the cataract
86 surgery had similar color discriminability compared to their contrast sensitivity matched
87 sighted controls. However, despite this initial evidence, these studies either exclusively used
88 shortly deprived individuals (< 6 months (Maurer et al., 1989)) or were not sensitive to the

89 identification of color deficits along specific color axes (i.e. long, middle, and short wavelength
90 axes) (McKyton et al., 2015).

91 Given that the detailed psychophysical and electrophysiological investigation of neural
92 mechanisms related to color processing in sight recovery individuals pose logistical challenges
93 (such as poor vision, specific hardware/software requirements), as a first step, it is imperative
94 to exclude any major color vision deficits across any specific color axes in sight recovery
95 individuals. To that end, we took advantage of a tertiary eye care set up and used the
96 Farnsworth D15 color vision test, which allowed us to identify possible axis specific and
97 unspecific color vision deficits. We tested a group of individuals who were diagnosed with
98 bilateral dense congenital cataracts (hereafter referred to as CC), bilateral developmental
99 cataracts or incomplete congenital cataracts (hereafter referred to as DC), and sighted control
100 (SC) participants with normal or corrected to normal visual acuity. Participants in both CC and
101 DC groups underwent cataract surgery with intraocular lens implantation and optical
102 correction. Since our *a priori* hypothesis predicted a null result, we additionally included a
103 group of individuals who were known to have congenital color vision defects as a positive
104 control. We hypothesized that CC individuals would have similar color discrimination
105 performance to DC and SC individuals.

106 **Methods**

107 **Participants**

108 All participants were recruited and tested at The LV Prasad Eye Institute, Hyderabad,
109 India (LVPEI). The CC group comprised of 12 participants (6 females, mean age: 17.58 years,
110 range: 8 – 33 years, mean age at surgery: 78.83 months, range: 4 – 218 months; mean logMAR

111 visual acuity: 0.69, range: 0.29 – 1.29). The history of bilateral dense congenital cataracts was
112 confirmed by medical records. In addition to the clinical diagnosis, factors such as presence of
113 sensory nystagmus, absence of fundus view prior to surgery, and positive family history, aided
114 in the classification of CC participants. Our control samples included two groups. The DC group
115 consisted of 10 participants (6 females, mean age: 14.5 years, range: 9 – 37 years; mean
116 logMAR visual acuity: 0.30, range: 0 to 1.04). This group served as control for visual
117 impairments and other effects related to a history of cataracts. The SC group included 14
118 participants (6 females, mean age: 17.86 years, range: 7 – 27 years). Additionally, we tested 4
119 participants (2 females, median age: 19 years, range 13 –28 years) who were known to have
120 congenital color deficiency. The participant characteristics of CC and DC groups are given in
121 the table below (Table 1).

122 All participants or their legal guardians (in case of minors) provided written informed
123 consent prior to taking part in the study. Participants or the legal guardians were reimbursed
124 for the study participation related expenses such as travel costs. Minor participants received
125 a small gift. The study protocol adhered to the tenets of Declarations of Helsinki (World
126 Medical Association, 2013). The study was approved by the Local Ethical Commission of the
127 Faculty of Psychology and Movement Sciences, University of Hamburg, Germany, as well as
128 the Institutional Ethical Review Board of LVPEI.

129 Test procedure

130 Figure 1 shows the Farnsworth D15 test used in the present study. The test panel containing
131 the color chips was displayed on a black background, and participants viewed the targets
132 binocularly. The D15 test contains a total of 16 caps (colors of which were designed such that
133 they are isoluminant on the CIE diagram). Out of these 16 caps, the reference cap (indicated

134 by the arrow in Fig. 1) is fixed, and rest of the 15 caps are movable. All of the movable caps
135 are numbered in their backside. At the beginning of the test, all caps were randomly jittered
136 and kept on a black sheet, and the participants were required to keep the cap that closely
137 matches the reference cap next to the reference cap. Then, the participant took the next cap
138 that most closely resembled the previous cap and moved it next to the previous cap. This
139 procedure was repeated for all remaining movable caps. A perfect arrangement of caps by a
140 color normal person is shown in Figure 1 *top panel*, whereas Figure 1 *bottom panel* shows the
141 arrangement of caps by a participant with a color vision defect.

142 Participants performed the test on their own pace. Once participants had arranged all
143 of the caps, the panel was **turned over**, and the numbers on their backs were recorded on a
144 recording sheet. These numbers corresponded to the positions of the tested color chips along
145 the hue circle. The order of the colors in the D15 panel are designed in a manner such that
146 specific color deficiencies would produce specific cap arrangements, in which, connecting
147 their cap numbers in the recording sheet will produce lines along one of the confusion axes of
148 dichromats (See *red*, *green*, and *blue* dotted lines in Fig. 2A-C). This aspect of the test provides
149 the diagnostic value towards identifying a specific color defect. If there were any errors,
150 participants were required to repeat the test, and their repeat measurement was taken for
151 the analysis. The entire test took approximately 10 minutes.

152 **Vector Analysis of D15**

153 As a clinical test, visual inspection of the D15 recording sheet was used to qualitatively
154 identify a color vision defect. However, we were interested in the quantification of color vision
155 defects, if present. Hence, we used the vector based quantification method proposed by

156 Vingrys and King-Smith (1988) to derive the following parameters: (1) confusion angle which
157 indicates the type of color defect, (2) confusion index which reveals the degree of color loss
158 relative to a perfect arrangement of caps, and (3) selectivity index, which reflects the polarity
159 and lack of randomness in a cap arrangement, and (4) a total error score.

160 A detailed procedure of the vector analysis can be found elsewhere (Vingrys & King-
161 Smith, 1988). Briefly, each test cap value was transposed into 1976 CIE color space and color
162 difference vectors between adjacent caps were calculated. All of these relative color
163 difference vectors were plotted such that normal color vision resulted in a scatter around the
164 origin, whereas different color vision defects produced color difference vectors that aligned
165 themselves in distinct axes. Assuming these color difference vectors as “rigid, weightless
166 bars”, *major* and *minor moments of inertia* of this vector plot can be calculated along its
167 principal axes (for details, see Fig. 4 in Vingrys & King-Smith, 1988). The axis angle that
168 produced *minimum moment of inertia* determined the confusion angle, whereas the length of
169 the *major radius of gyration* yielded the confusion index, and the ratio of *major* and *minor*
170 *radii of gyration* was calculated as the selectivity index. Figure 2A and 2B show the panel
171 arrangements and their color vision metrics by individuals with normal color discrimination
172 and deutan color deficiency, respectively. A perfect arrangement indicating normal color
173 discrimination resulted in the following values: - confusion index: 1, total error score: 11.42,
174 confusion angle: 61.98, and selectivity index: 1.38. The usefulness of this vector based
175 technique is illustrated in Figure 2C and Figure 2D: Figure 2C shows multiple random errors
176 with diametric crossings but not specific to any color confusion axes, while 2D displays a single
177 small error along the protan axis. Hence, the confusion index and total error score of 2C were
178 greater than in Figure 2D, however, the selectivity index of 2D was greater than in Figure 2C.

179 Custom written software in Matlab™ version 8 (The MathWorks, Inc., Natick, MA, USA) was
180 used to perform the above mentioned analysis. The software is available upon request.

181 **Statistical analysis**

182 Since the data did not follow a normal distribution, between-group comparisons were
183 tested using Kruskal-Wallis (KW) test, and separate KW tests were run for each of the four
184 dependent variables (i.e. total error score, confusion index, confusion angle, and selectivity
185 index). Formal statistics were conducted using IBM SPSS Statistics 20 (SPSS Inc., Chicago, IL).
186 The data from color deficient individuals were used to demonstrate the ability of our set up
187 to isolate color vision deficiencies, and not included in the formal data analysis.

188 **Results**

189 The following table (Table 2) summarizes the descriptive statistics of the measured
190 color vision indices (total error score, confusion index, confusion angle, and selectivity index)
191 across the CC, DC, SC groups.

192 Figure 3 shows the measured color vision indices in CC, DC, and SC individuals (along
193 with median and inter-quartile range). All four color indices were indistinguishable between
194 the CC, DC, and SC groups (Total error score: $\chi^2(2) = 4.24$, $p = 0.12$; Confusion index: - $\chi^2(2) =$
195 4.02 , $p = 0.13$; Confusion angle: $\chi^2(2) = 1.57$, $p = 0.46$; selectivity index: $\chi^2(2) = 1.92$, $p = 0.38$).

196 Individuals with congenital color vision deficiencies ($n = 4$, filled symbols in Fig. 3)
197 markedly differed from the CC, DC, and SC groups, and did not overlap with these groups in
198 terms of their total error score (color vision deficiencies range: 29.28 to 37.71), confusion

199 index (color vision deficiencies range: 2.88 to 4.03), and confusion angle (3.86 to -52.76). The
200 confusion angles of congenital color deficient individuals indicated that two of them had
201 deficiency along the protan axis (3.86, and 5.31), one of them had deficiency along the deutan
202 axis (-13.47), and the remaining participant had deficiency along the tritan axis (-52.76). Based
203 on the selectivity index, two of the four congenital color deficiency individuals had relatively
204 selective losses along their respective axes (4.41 and 5.93) compared to the other two
205 individuals (2.16 and 1.25).

206 **Discussion**

207 The goal of the present study was to examine the effect of transient congenital visual
208 deprivation on the development of color vision as measured using Farnsworth D15 test. To
209 that end, we quantified different color vision metrics in a distinct group of individuals who had
210 a period of severe visual deprivation due to dense bilateral congenital cataracts (CC) and
211 compared them to two control groups. The first control group comprised of individuals who
212 had developed cataract later in their childhood (i.e. developmental cataract, DC) or had a
213 history of non-dense congenital cataract, and the second group of individuals with normal or
214 corrected to normal visual acuity (i.e. sighted controls, SC). All of the computed color vision
215 metrics, namely total error score, confusion angle, confusion index, and selectivity index did
216 not differ between CC, and DC, SC individuals (Fig. 3). Thus, our findings strongly argue against
217 a sensitive period for the development of basic color discrimination and color arrangement.

218 Our results extend previous reports on color processing in sight recovery individuals
219 after a short (Maurer et al., 1989) or long (McKyton et al., 2015) period of visual deprivation
220 from birth due to cataracts. The methods used by both Maurer et al. (1989) and McKyton et

221 al. (2015) were not sensitive to identify any possible axis specific color vision defects, and it is
222 important to note that congenital color deficiencies are usually axis specific (Simunovic, 2010),
223 as indicated by the individuals in our color deficiency group. In addition, the experimental
224 paradigm of McKyton et al. (2015) randomly sampled the color space (hue values) at fixed,
225 pre-determined intervals, hence, it is unclear how individuals with known color vision deficits
226 would have performed in this paradigm. For example, the probability of sampling someone's
227 deficient color axis might affect the goodness of fit of the psychometric function itself, rather
228 than exclusively moving the psychometric function to the right, producing an elevated hue
229 difference threshold.

230 To address the above-mentioned limitations, we took the following steps in our study
231 design and analysis. Firstly, we included CC individuals with more extensive periods of visual
232 deprivation (mean age at surgery: 83.6 months; range: 4 - 396 months) compared to Maurer
233 et al. (1989) and McKyton et al. (2015). Secondly, we calculated two color metrics that would
234 indicate any axis specific color deficits, namely confusion angle and confusion index. Both of
235 these metrics were unaffected by a transient period of sensory deprivation. Thirdly, we
236 included individuals with developmental cataracts as a control group, and this group served
237 as control for visual impairment and other effects that were related to a history of cataract
238 and cataract surgery (for e.g. differential wavelength absorption characteristics between
239 human crystalline lens and implanted intraocular lens (Davison, Patel, Cunha, Schwiegerling,
240 & Muftuoglu, 2011). Finally, we tested a group of individuals with known congenital color
241 vision deficiencies, who were appropriately isolated by our current testing setup.

242 Our results might suggest two possible speculative explanations regarding the role of
243 visual experience on the development of color discrimination: (1) the neural mechanisms that

244 are responsible for the color discrimination can start developing later in adulthood, once visual
245 input is available, or (2) these mechanisms mature irrespective of the presence of visual input.
246 While our data do not allow to decide between these two accounts, it could be argued that
247 color discrimination abilities recover after sight restoration based on the following
248 observation: In the study of McKyton et al. (McKyton et al., 2015), some of the “late treated
249 cataract” individuals were tested immediately after (or within weeks of) the cataract surgery,
250 during which they showed elevated color discrimination thresholds compared to their control
251 participants. However, their color discrimination thresholds reached the values that were
252 similar to that of the sighted control participants when tested 1 year after the surgery. These
253 data, together with our results, suggest that color vision evolves without early visual input
254 during the first months of life. Furthermore, newborns aged 1 to 7 days (Adams & Courage,
255 1998) as well as young infants aged 1 to 3 months (Hamer, Alexander, & Teller, 1982; Packer,
256 Hartmann, & Teller, 1984) were able to discriminate chromatic light from achromatic light,
257 tested using preferential looking methods, and categorization of basic hues (and their
258 boundaries) seems to be adult-like in 4 month old infants (Bornstein, Kessen, & Weiskopf,
259 1976). These results suggest an early development of color discrimination despite immature
260 cones (Yuodelis & Hendrickson, 1986). Hence, long deprivation does not seem to result in a
261 loss or irreversible damage, neither at the peripheral nor at the central processing level.

262 Accurate measurement of color discrimination is a challenging task since the non-color
263 related cues, such as luminance, can aid color discrimination, and generating isoluminant
264 patterns has specific hardware requirements. Here, we have taken advantage of a
265 standardized clinical test of color discrimination, namely the Farnsworth D15 panel test. The
266 D15 test is an easily comprehensible test which needs less than 10 minutes of testing for

267 completion. This test does not require the participants to be familiar with numerals in a
268 specific script, unlike the pseudo-isochromatic plate tests, such as Ishihara. These advantages
269 of accessibility and short testing duration are important, as our testing population was a
270 special clinical population with a wide age range including children.

271 Although we used a standardized clinical test employed for color assessment, and a
272 widely used vector based method (Vingrys & King-Smith, 1988) for quantifying color metrics,
273 there is a potential limitation that needs to be addressed here. The study was conducted at a
274 regular clinical set up under the normal room lighting (correlated color temperature: 5637°K,
275 illuminance: 140.4 lux measured using X-Rite i1 Display Pro™ color calibration device), rather
276 than the standard Illuminant C or Macbeth Easel Lamp that is considered to provide a stable
277 approximation of the natural daylight. Although it has been shown that some fluorescent
278 lamps are comparable to Illuminant C for the purposes color testing (Hovis & Neumann, 1995),
279 we additionally tested the ability of our set up to identify individuals with known congenital
280 color vision deficits. For this purpose, we tested 4 congenitally color blind participants, and
281 our set up was able to pick up all of the congenital color deficiencies.

282 In conclusion, the present results showed that the major color vision indices were
283 unaltered by a period of congenital visual deprivation, extending previous findings from
284 human and non-human studies (Boothe et al., 1975; Brenner et al., 1990, 1985; Maurer et al.,
285 1989; McKyton et al., 2015; Petry & Kelly, 1991). Therefore, our data strongly argues against
286 a sensitive period for the development of color discrimination.

287

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295

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362

363 **Tables:**

364 **Table 1. Participant characteristics of CC and DC group (BCVA- Best corrected visual acuity)**

Participant ID	Age (years)	Gender	Cataract type	Age at surgery (months)	BCVA (logMAR acuity)
CC-01	26	Male	Congenital	5	0.74
CC-02	33	Male	Congenital	276	1.29
CC-03	11	Female	Congenital	72	0.59
CC-04	23	Male	Congenital	4	0.89
CC-05	21	Male	Congenital	213	0.70
CC-06	10	Male	Congenital	11	0.40
CC-07	10	Female	Congenital	42	0.35
CC-08	8	Female	Congenital	4	0.29
CC-09	18	Female	Congenital	25	0.51
CC-10	13	Male	Congenital	64	0.59
CC-11	19	Female	Congenital	225	1.03
CC-12	19	Female	Congenital	225	0.89
DC-01	9	Female	Developmental	77	0.30
DC-02	13	Male	Developmental	96	0.15
DC-03	37	Female	Non dense CC	396	1.04
DC-04	14	Female	Developmental	90	0.28
DC-05	11	Female	Developmental	99	0.28
DC-06	12	Male	Developmental	100	0.22

DC-07	13	Male	Developmental	143	0.11
DC-08	16	Male	Developmental	146	0.00
DC-09	9	Female	Developmental	76	0.64
DC-10	11	Female	Developmental	91	0.00

365

366 *Table 2: summary measures of calculated color vision indices. CC- bilateral dense congenital*
367 *cataract; DC- bilateral developmental cataract/incomplete congenital cataract; SC- sighted*
368 *controls*

	CC		DC		SC	
	median	range	median	range	median	range
Total error score	11.42	11.42 - 16.51	11.42	11.42 - 23.01	11.42	11.42 - 12.45
Confusion index	1	1.00 – 1.62	1	1.00 - 1.83	1	1.00 - 1.13
Confusion angle	61.98	46.54 - 61.98	61.98	48.10 - 75.10	61.98	53.00 - 61.98
Selectivity index	1.38	1.38 - 2.11	1.38	1.08 - 1.85	1.38	1.38 - 1.53

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371 **Figure captions:**

372 Fig. 1. Farnsworth D15 panel used for the testing of color vision. The left most chip indicated
373 by the white arrow is the fixed reference panel. The top panel shows the caps arranged by an
374 individual with normal color vision and the bottom panel shows the cap arrangement by an
375 individual with color deficiency

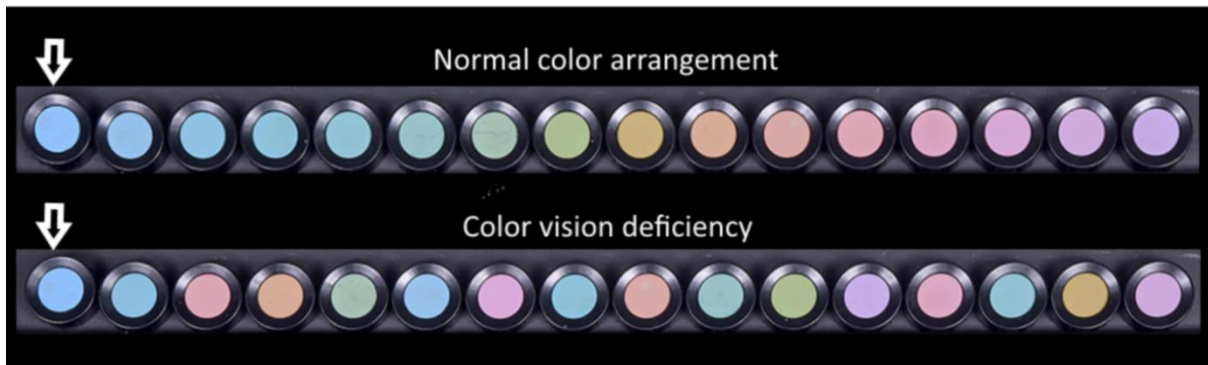
376 Fig. 2. Examples of D15 panel arrangements by participants and their corresponding color
377 vision indices. The red, green, and blue lines indicate long, middle, and short wavelength
378 confusion axes, respectively. Cap arrangements by individuals with normal color
379 discrimination (A), deutan (middle wavelength deficit) error (B), random errors unspecific to
380 any color axis (C), a minor error along the protan (long wavelength deficit) axis (D)

381 Fig. 3. Comparison of color vision indices across groups (individual data with median and inter-
382 quartile range; CC- bilateral dense congenital cataract; DC- bilateral developmental
383 cataract/incomplete congenital cataract; SC- sighted controls; CD- individuals with a
384 congenital color deficiency.

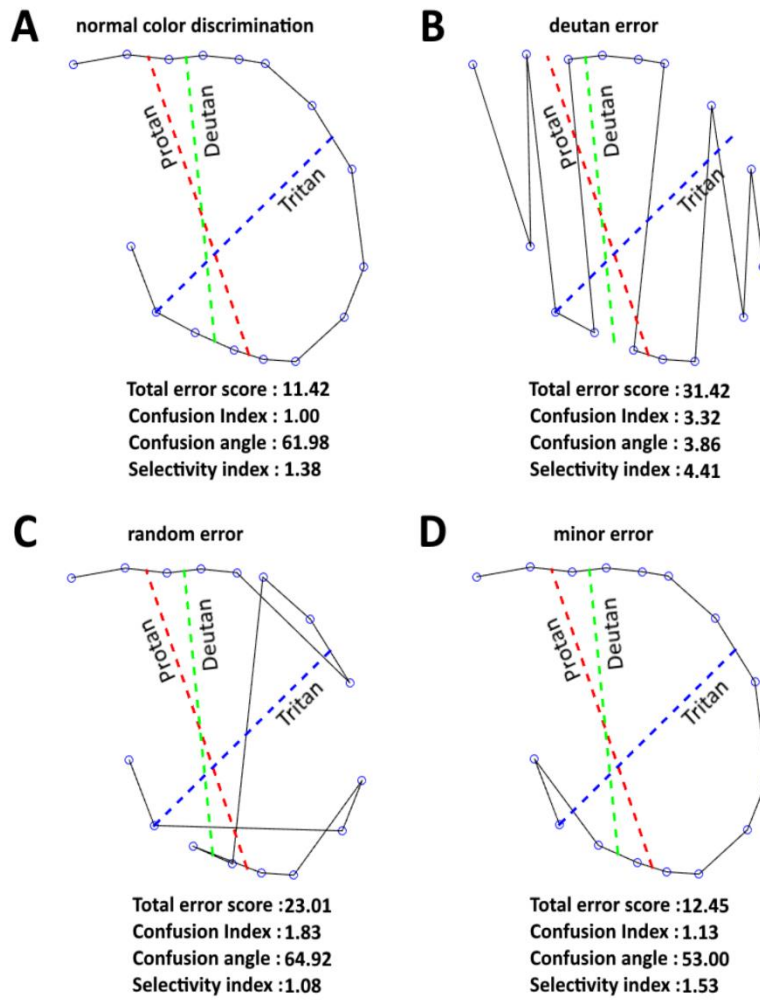
385

386 **Figures:**

387 **Fig. 1**



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