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1 **Color Vision Assessment – 1. Visual signals that affect the results of the Farnsworth D-**  
2 **15 test**

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20 **Abstract:**

21 The Farnsworth D-15 test (D-15) is commonly used to screen for moderate to severe  
22 congenital color vision deficiency. The aim of this study was to establish reliable D-15  
23 statistics for normal, deutan and protan subjects, and to investigate the different visual signals  
24 one can use to carry out the test, even in dichromats and rod monochromats. Six hundred and  
25 seventy-four subjects were examined using the D-15, the Colour Assessment & Diagnosis  
26 (CAD) test and the Nagel anomaloscope. A rod monochromat and five dichromats were  
27 tested using the standard D-15 protocol before the caps were separated into two groups and  
28 subjects were asked to repeat the task. D-15 spectral radiance data, measured under D65  
29 illumination, were used to estimate differences in photoreceptor excitations for each of the  
30 caps. When no crossings and up to two adjacent transpositions on the D-15 results diagram  
31 are accepted as a pass, 100% of normal trichromats, 54% of deuterans and 43% of protans pass  
32 the D-15. A rod monochromat and two protanopes and deuteranopes were able to complete  
33 the D-15 when the caps were separated into two groups, despite severe loss or even complete  
34 absence of color vision. When up to two adjacent transpositions are accepted 50% of color  
35 deficient subjects, some with severe red/green loss, pass the D-15. Whilst the D-15 is  
36 normally used to screen for moderate to severe color deficiency, subjects with severe loss can  
37 still use combined, residual red/green, yellow/blue and luminance signals to pass.

38

39 **Keywords:** Farnsworth D-15, color assessment, color vision deficiency, dichromatism, rod  
40 monochromatism

## 41 **1. Introduction**

42 This is the first in a series of three papers which examined common color assessment tests  
43 employed in the clinic to detect early changes in chromatic sensitivity and also in occupations  
44 to screen for congenital and / or acquired loss of color vision in order to relate test outcomes  
45 to class and severity of color vision loss. This paper evaluates the performance of the  
46 Farnsworth D-15 test (D-15) at screening for and classifying color vision deficiency, in  
47 addition to appraising the residual signals that enable subjects with reduced chromatic  
48 sensitivity to successfully arrange the caps. The second paper<sup>1</sup> evaluates the statistical  
49 outcomes of commonly used color assessment tests and examines the efficiency of frequently  
50 used single- and multi-test protocols. The third paper<sup>2</sup> assesses the fundamental limits of what  
51 one can achieve in color vision assessment and describes a new test that approaches this limit.  
52 Following its introduction over 70 years ago<sup>3</sup> the D-15 continues to be used to screen for  
53 individuals with reduced chromatic sensitivity in occupational and clinical environments<sup>4-8</sup>.  
54 The standard D-15 consists of 16 Munsell hues, mounted in circular casings or ‘caps’, of  
55 approximately 13mm in diameter. Participants are provided with a fixed reference or pilot  
56 cap and are asked to select and arrange the remaining caps, one by one, in each instance  
57 selecting the cap that appears to be least-different perceptually to the most recently selected  
58 cap<sup>9</sup>.  
59 Various methods for establishing error scores have been described<sup>10-13</sup> and in a recent study,  
60 the type and number of errors subjects make have even been related with some success to the  
61 colorimetric characteristics of the caps<sup>14</sup>. In spite of such efforts, the preferred method of  
62 interpreting the results of the D-15 in most clinical settings is to plot the subject’s arranged  
63 sequence on a circular diagram<sup>15,16</sup>. The circular diagram plays a large role in the ease of  
64 administration and interpretation of the results. Errors made on the D-15 are classified, based  
65 upon their appearance when plotted on the circular diagram, as either being adjacent

66 transpositions or major isochromatic crossings. Commonly used ‘pass’ protocols vary  
67 between accepting 1-2 adjacent transpositions<sup>17</sup> to allowing up to 2 major isochromatic  
68 crossings<sup>18</sup>; these types of errors are illustrated in more detail in Figures 1c and d.  
69 Monochromats, dichromats and anomalous trichromats with reduced or absent chromatic  
70 sensitivity are expected to fail, making multiple crossings, whilst those who pass are assumed  
71 to have normal trichromatic color vision or close to normal chromatic sensitivity<sup>8,9,19</sup>, making  
72 at most one to two adjacent transpositions.

73 The Colour Assessment and Diagnosis (CAD) test is a color detection threshold test based on  
74 findings from studies designed to investigate how the spatiotemporal characteristics of the  
75 background field can be used to desensitise either luminance or chromatic mechanisms<sup>20,21</sup>.  
76 Further studies on camouflage revealed new ways to isolate the use of color signals without  
77 affecting significantly the sensitivity of chromatic mechanisms<sup>22,23</sup>. The standardised version  
78 of the CAD test displays moving stimuli buried in dynamic luminance contrast noise and the  
79 output is measured in terms of red/green (RG) and yellow/blue (YB) color thresholds<sup>24</sup> that  
80 are approximately linearly proportional to the cone contrasts generated by the colored  
81 stimulus<sup>25</sup>. The Nagel anomaloscope, when carried out by a trained examiner in the clinic, is  
82 considered to be the most accurate test for determining and classifying deutan and protan  
83 deficiency<sup>9,26</sup>. Although the disagreement between the anomaloscope matching range and the  
84 outcome of the D-15 test has been previously documented by Birch<sup>27</sup>, the study used the size  
85 of the Rayleigh match as a measure for the severity of loss. Whilst the Nagel anomaloscope is  
86 renowned for its accuracy in distinguishing between protanomalous and deuteranomalous  
87 observers<sup>28,29</sup>, the relationship between the parameters of the match and the subject’s overall  
88 chromatic sensitivity is known to be generally poor<sup>30</sup>.

89 The limitations of the D-15, including the potential effects on the D-15 from variation in  
90 illuminants, have recently been highlighted<sup>31</sup> and the impact that practice can have on the

91 outcome of the D-15, and the subsequent suitability of the D-15 have been questioned<sup>32,33</sup>.  
92 Given the extensive use of the D-15 in the clinic, and particularly in occupational settings, the  
93 test still has relevance today. It is important to note, and appreciate, in most clinical and  
94 occupational settings, the D-15 is employed as a secondary test, used if applicants fail an  
95 initial screening test, such as the Ishihara pseudoisochromatic plate test<sup>34</sup>. The principal aim  
96 of this study is to evaluate the performance of the D-15 test at screening for and classifying  
97 color vision deficiency and to examine the spread in the severity of color vision loss in those  
98 who fail and those who pass the most commonly used D-15 protocols. Since many subjects  
99 with severe RG color deficiency pass the D-15 test, a secondary aim of the project is to  
100 identify the residual signals that enable these subjects to successfully arrange the caps.

## 101 **2. Methods**

102 Data for 850 subjects were abstracted from anonymized records collected through the  
103 Advanced Vision and Optometric Tests (AVOT) clinic service at City, University of London.  
104 All subjects completed the D-15, CAD test and Nagel anomaloscope. Standardised  
105 instructions were given prior to all tests. The exclusion criteria were acquired colour vision  
106 loss, subjects under 10 years of age, and subjects who returned to the AVOT clinic for  
107 multiple assessments. For subjects who returned for repeat visits, only the data from their first  
108 visit were used. Following application of the exclusion criteria, the results for 395 deuterans,  
109 205 protans and 74 normal trichromats were evaluated. The age of subjects ranged from 10 to  
110 65 years. Diagnosis of the type of color vision deficiency was determined from the results of  
111 the CAD test and the Nagel anomaloscope.

112 The D-15 was illuminated with the new Macbeth easel lamp approximating CIE illuminant  
113 D65. The mean luminance of the caps was 16.6 cd/m<sup>2</sup> (SD = 0.45, range: 15.7 to 17.5 cd/m<sup>2</sup>).  
114 A magnesium oxide reference white surface (R = ~0.94) had a luminance of 87.8 cd/m<sup>2</sup> and

115 CIE 1931 chromaticity of 0.306, 0.324. This corresponds approximately to an illuminance  
116 level of 293 lm/m<sup>2</sup>.

117 Subjects were instructed to initially select the cap that appeared to be most similar to the pilot  
118 or reference cap, and then to select the cap that appeared to be most similar to the last cap that  
119 they selected. Upon completing the test subjects were asked to review their arrangement and  
120 make any changes, if desired. No feedback was provided during the assessment.

121 The CAD test employs a 10 bit Eizo CS2420 monitor calibrated for luminance and the  
122 chromaticity of each primary color using a Konica CS-2000A telespectroradiometer  
123 (manufactured by Konica Minolta Inc. with a spectral range of 380 to 780nm. The spectrum  
124 was sampled every nm with a bandwidth of just under 1nm). The CAD test runs on an HP  
125 ProBook 650 G1 laptop. The standard CAD test uses 16 interleaved color directions specified  
126 in CIE 1931 color space. Following each presentation, the subject's task was to press one of  
127 four buttons, to indicate the direction of motion of the color-defined stimulus<sup>24</sup>. Before  
128 completing the CAD test all subjects were required to complete a short 'learning mode'  
129 correctly, to ensure they understood the task. A Type I Nagel anomaloscope was used to  
130 measure the Rayleigh color match for all subjects.

131 The outcome of the D-15 was evaluated using two pass criteria, allowing no errors (either  
132 major crossings or adjacent transpositions) and accepting up to two adjacent transpositions as  
133 a pass on the D-15, in order to pass all normal subjects, as diagnosed by the CAD test and the  
134 Nagel Anomaloscope, in the sample. The D-15 classification was determined by splitting the  
135 cap order into 15 pairs of sequential caps and passing each pair through a classification grid  
136 (Figure 1a). RG CAD thresholds were used to evaluate the relationship between the severity  
137 of loss in protans and deutans and the outcome of the D-15.

138 The spectral radiance of each cap when illuminated with D65 was measured using the Konica  
139 CS-2000A telespectroradiometer. The spectral radiance data were used in combination with

140 the Smith and Pokorny cone fundamentals<sup>35</sup> to estimate cap-specific cone excitations. The  
141 spectral luminous efficiency function,  $V'(\lambda)$ , was used to calculate the corresponding rod  
142 photoreceptor excitations<sup>36</sup>.

143 To investigate the residual signals that enable subjects with severe RG deficiency to  
144 successfully arrange the D-15 caps we established whether in the absence of normal RG  
145 chromatic signals, sequential, monotonic step changes in S cone and rod signals between  
146 adjacent caps can provide sufficient information to enable dichromats and rod monochromats  
147 to order the caps correctly by minimising the perceptual differences between adjacent caps.  
148 To do this, two reduced versions of the D-15 task were created. The illumination was kept  
149 constant and no new caps were introduced. The 16 caps employed in the D-15 test were split  
150 into two cap subgroups. Given the aim of investigating those with severe RG loss the two cap  
151 subgroups were selected based on the measured S-cone and rod excitations shown in Figure  
152 3d. The first cap subgroup (caps P-8) exhibit monotonic decrements in S-cone and rod  
153 signals, whilst the second cap subgroup (caps 9-15) exhibit positive monotonic increments in  
154 S-cone and rod excitations. Note that caps 9 and 10 exhibit approximately equal rod  
155 excitations.

156 A rod monochromat, with a visual acuity of 20/200, identified as CNGB3 through genetic  
157 testing at Moorfields Eye Hospital London, a tritanope, two protanopes and two deuteranopes  
158 were assessed using the two D-15 protocols. The protanope and deuteranope were identified  
159 using the Nagel anomaloscope. The tritanope was identified using the CAD test, in which the  
160 subject displayed normal RG color thresholds, but exhibited specific loss along the tritan  
161 confusion axis that was only limited by the maximum chromatic displacements that can be  
162 achieved on the visual display, see Figure 6c. These subjects completed the standard D-15  
163 protocol before the caps were separated into two cap subgroups, from caps P-8 and caps 9-15,  
164 and subjects were asked to arrange the caps in each cap subgroup as to minimise the

165 perceived differences between each cap, repeating the D-15 protocol with a reduced selection  
166 of caps. All subjects arranged the two subgroups within two minutes of being presented with  
167 the caps. Informed consent was obtained from all subjects. The study was conducted in  
168 compliance with the City, University of London research and ethical guidelines and followed  
169 the tenets of the Declaration of Helsinki.

### 170 **3. Results**

171 When no crossings and no adjacent transpositions are accepted, 99% of normal trichromats,  
172 66% of deuteranomalous trichromats, 60% of protanomalous trichromats, 2% of  
173 deuteranopes and 3% of protanopes pass the D-15. When no crossings and up to two adjacent  
174 transpositions are accepted, 100% of normal trichromats pass the D-15. The percentage of  
175 subjects with congenital color vision deficiency who pass the D-15 are shown in Table 1a.

176 When up to two adjacent transpositions are accepted, 76% of deuteranomalous trichromats,  
177 69% of protanomalous trichromats, 3% of deuteranopes and 9% of protanopes pass the D-15.

178 Approximately 74% of anomalous trichromats in this cohort pass, whereas only ~6% of  
179 dichromats pass (Table 1b), and 54% of deutans pass compared to 43% of protans (Table 1c).

180 There was 100% agreement between the classification made by the CAD test and the Nagel  
181 anomaloscope for all subjects in this study. The classification made by the D-15 in all

182 subjects and in those that fail the D-15, when up to two adjacent transpositions are accepted,  
183 is shown in Table 2a and Table 2b, respectively. For all subjects the D-15 correctly classifies

184 94.9% of deuteranopes, 80.9% of protanopes, and 19.8% and 21.6% of deuteranomalous and  
185 protanomalous trichromats, respectively. The classification made by the D-15 improves if

186 one only considers those who fail the D-15, when up to two adjacent transpositions are  
187 accepted, with 98.2%, 88.9%, 80.9%, and 69.5% of deuteranopes, protanopes,

188 deuteranomalous trichromats, and protanomalous trichromats respectively being classified  
189 correctly.

190 All subjects within the cohort had YB CAD thresholds within the normal range for their age.  
191 The distributions of RG CAD thresholds in deuterans and protans who pass and fail the D-15  
192 are shown in Figure 2. The median RG CAD thresholds for deuterans that pass the D-15 was  
193 5.93 RG CAD units and 10.38 RG CAD units for protans. One CAD unit describes the  
194 median RG or YB threshold color signal strengths measured in 330 healthy, young, normal  
195 trichromats<sup>24</sup>. Only 50% of normal trichromats have thresholds less than one CAD unit. The  
196 maximum RG CAD threshold for those who passed the D-15, when up to two adjacent  
197 transpositions were accepted, was 25.81 for deuterans and 24.69 RG CAD units for protans.  
198 The predicted photoreceptor excitations generated by the D-15 caps are shown in Figure 3d.  
199 When two protanopes and two deuteranopes completed the D-15 under the standard protocol  
200 their results produced typical error patterns, with participants making multiple major iso-  
201 chromatic crossings (Figure 4b and Figure 5b). When the caps were separated into two  
202 subgroups, both protanopes and deuteranopes were able to arrange the caps within each  
203 subgroup with no errors. When a tritanope completed the same protocol, they were unable to  
204 arrange the caps correctly under standard conditions. This was also the case when presented  
205 with each of the two subgroups (Figure 6b).  
206 Not unexpectedly, a rod monochromat (CNGB3) made several errors on the D-15 test under  
207 normal conditions (Figure 7b). When presented with each of the two subgroups, the rod  
208 monochromat was able to arrange the caps almost completely correctly, only making one  
209 minor transposition (cap 9 and 10 during the first test and interchanging the order of these  
210 two caps in repeated tests). These caps have approximately the same rod excitation, see  
211 Figure 7d.

#### 212 **4. Discussion**

213 The D-15 pass rates obtained in this study, when up to two adjacent transpositions are  
214 accepted, are slightly higher than previous reports, with a similar sample size (N=710), by

215 Birch<sup>16</sup> using a ‘circular results diagram’ and accepting a maximum of two adjacent  
216 transpositions, and higher than Dain and Adams<sup>37</sup>, who used a significantly smaller sample  
217 size (N=75). Several factors may contribute to this difference, notably the range of severity of  
218 loss in the sample and the method of collecting data. As shown in Figure 2 the cohort  
219 examined in this study contains a large number of mild protans and deutans, (particularly  
220 deutans) with relatively low RG CAD thresholds. Although the cohort contains some younger  
221 individuals, previous studies have shown that children aged from 5-12 years are capable of  
222 performing color arrangement tests such as the D-15, albeit with a modified protocol<sup>38</sup>.  
223 However, in more complex tests such as the Farnsworth-Munsell 100-Hue, results in children  
224 can also be affected by their nonverbal IQ<sup>39</sup>.

225 The two pass criteria investigated highlight the balancing act and limitation present in all tests  
226 with variable pass criteria; the maximisation of both sensitivity and specificity. The maximal  
227 sensitivity of the D-15 is obtained when one accepts no errors on the D-15 test and, based  
228 upon data collected in this study, the specificity is maximised when up to two adjacent  
229 transpositions are accepted. Particularly in occupational settings a small number of adjacent  
230 transpositions are typically accepted in order to ensure that the small percentage of normal  
231 trichromats who make such errors pass the D-15, even if this is at the cost of passing more  
232 individuals with color vision deficiency<sup>1</sup>. From the data in this study, by accepting adjacent  
233 transpositions, and passing the 1% of normals who make such errors, one is also allowing  
234 approximately 10% more anomalous trichromats and 3% more dichromats to pass the D-15.

235 It is important to also consider the manner in which the data were collected. Most individuals  
236 who attend the AVOT service at City, University of London do so to complete a color vision  
237 assessment to determine whether they pass an occupational color vision standard. Many of  
238 these individuals will have previously failed some form of screening test (typically the  
239 Ishihara pseudoisochromatic plate test), and although not formally quantified, it is highly

240 likely that some of the individuals in this sample will have encountered other conventional  
241 color vision tests (such as the City University test or the D-15), prior to coming to the AVOT  
242 service. The impact of practicing the D-15 has been recently discussed in two publications by  
243 Ng and Liem<sup>32</sup> and Ng and Morton<sup>33</sup> who demonstrated that color deficient subjects,  
244 including dichromats, who initially made errors on the D-15 were able to complete the test  
245 correctly after practicing the test. Dain, Atchison and Hovis<sup>31</sup> build upon these ideas and also  
246 highlight the potential impact the choice of illumination may have upon the outcome of the  
247 D-15. The confounding variable of practice effects and their influence on repeatability and  
248 reproducibility is an issue with many conventional methods of color assessment, including  
249 the D-15.

250 These limitations are virtually impossible to control if one wishes to consistently use one  
251 version of the D-15; one cannot stop members of the public from completing the D-15 at  
252 other testing centres or practicing it in their own time. In multiple instances, we have seen  
253 applicants who receive an inconclusive color vision diagnosis at an occupational health care  
254 assessment and are referred to multiple optometrists for further color vision assessment,  
255 before being asked to visit the AVOT clinic at City, University of London. In such cases the  
256 applicant, through no fault of their own, has multiple opportunities to practice many  
257 conventional color vision tests, including the D-15 and to improve their performance by  
258 learning how to make better use of any additional cues.

259 The collection of CAD and D-15 data allows for the direct comparison between the outcome  
260 of the D-15 and the severity of loss, as quantified by RG CAD thresholds. This approach has  
261 been employed in a recently published study<sup>4</sup> designed to assess the spread in the severity of  
262 RG loss in deutan and protan subjects who pass and those who fail the D-15 test when using  
263 the Canadian Air Force color assessment protocol for the D-15 test. The results are similar in  
264 the two studies and reveal the large variability in the severity of RG color vision loss in both

265 those who pass and those who fail the D-15 protocol. The large difference in sample size, 395  
266 deutan and 205 protans examined in this study, and 40 deutan and 28 protans examined in  
267 the study by Almustanyir, Hovis and Glaholt<sup>4</sup> as well as the use of different protocols for the  
268 D-15, may account for the observed differences, particularly the fewer protans and deutan  
269 with less severe loss of RG color vision who fail. The median RG CAD threshold and the  
270 interquartile range are lower for subjects that pass the D-15, in both protan and deutan  
271 deficiencies (Figure 2a and b). As a consequence, at least 75% of subjects with a congenital  
272 color vision deficiency that are dichotomised by the D-15 are being split correctly, and fairly,  
273 based upon their RG chromatic sensitivity. This outcome is however of limited value since  
274 the D-15 also passes individuals with severe RG chromatic loss (with CAD thresholds up to  
275 25.81 RG CAD units) and fails some individuals with RG thresholds below 4.00 CAD units.  
276 These observations are of particular significance in occupational environments, where the  
277 outcome of the D-15 is used to determine occupational suitability in visually demanding  
278 jobs<sup>1,4</sup>.

279 The observed variability in RG chromatic sensitivity in color deficient subjects who pass and  
280 also in those who fail the D-15 test suggests that the subjects make use of multiple signals to  
281 carry out the task. The extent to which subjects make use of these signals will depend both  
282 on the signals available and the attention given to any additional clues, with the latter being  
283 minimised through the use of standardised instructions.

284 Given that all subjects had normal YB chromatic sensitivity (as measured by the CAD test), it  
285 is of interest to know the extent to which the subjects make use of YB color signal changes to  
286 pass the test. The expected changes in S-cone photoreceptor excitation when viewing the D-  
287 15 caps are shown in Figure 3d. The monotonic decrease in S-cone signals from the pilot cap  
288 to cap 8, hint at a potential answer. As one moves across the caps employed in the D-15 one  
289 observes a large change in the predicted S-cone photoreceptor signal, accompanied by a

290 slightly smaller change in the predicted rod-photoreceptor excitation. There is relatively low  
291 variation in the theoretical M- and L- cone photoreceptor excitation, by contrast, when one  
292 moves across the D-15 caps. The predicted photoreceptor excitations do not account for the  
293 relative number of photoreceptors in the eye, or post receptor processing. However, they do  
294 provide, at least on a basic level, an indication to the initial signals generated by the D-15  
295 caps at the earliest stages of visual processing.

296 A limitation of this approach is the consideration of only 4 categories of photoreceptor in the  
297 eye. Intrinsically photosensitive retinal ganglion cells (ipRGCs) have recently been shown to  
298 play a role in form vision in the peripheral retina<sup>40</sup> and their impact upon non-image forming  
299 visual functions has also been investigated in primate retina<sup>41</sup>. Due to the sparse distribution  
300 and large receptive fields involved, ipRGCs are unlikely to notably contribute towards the  
301 successful completion of the D-15 task, given the relatively small angular size of each cap  
302 and the foveal location of the primary image location<sup>42-44</sup>. The spectral responsivity of  
303 ipRGCs overlaps significantly with that of rods. Rod signals are the greatest signal  
304 contributor to ipRGCs. The light levels involved in D15 tests are low photopic and therefore  
305 most unlikely to involve melanopsin mediated signals. The results and conclusions drawn  
306 from our findings remain unchanged even if rod signals associated with ipRGCs contribute to  
307 the perceived brightness difference that help with the D15 task in rod monochromats. Further  
308 studies are required to fully establish the role ipRGCs may play in hue arrangement tasks,  
309 such as the D-15.

310 The results obtained from dichromats and a rod monochromat who also completed the two  
311 protocols demonstrate that protanopes, deuteranopes, and even rod monochromats are able to  
312 make use of the relatively large changes in S- cone and rod photoreceptor signals to complete  
313 the D-15 test. Protanopes and deuteranopes who make multiple isochromatic crossings under  
314 the standard D-15 protocol, made no errors when the caps were split into two groups. This is

315 not unexpected; the diminished or even absent RG color signal differences that prevent  
316 typical protan and deutan confusions, particularly major crossings, are no longer possible and  
317 caps with equal S-cone excitation are not available within either of the two cap subgroups.  
318 The results in the tritanope (Figure 6) suggest strongly that normal RG color signals are not  
319 sufficient to pass the D-15 test with no errors, since the tritanope makes multiple errors when  
320 presented with the full set of caps and also makes errors when presented separately with each  
321 of the two subgroups. The rod monochromat, on the other hand, can only rely on monotonic  
322 changes in rod signals which can be used effectively within each subgroup to arrange the  
323 caps in the correct sequence. The tritanope makes multiple errors within each subgroup, in  
324 spite of normal rod function. An interesting consequence of this finding is that either the  
325 presence of normal RG color signals or simply the interaction between M, L and rod signals  
326 reduces the effectiveness of monotonic rod signal changes to carry out the test.  
327 The results obtained in the rod monochromat merit further discussion. The results shown in  
328 Figure 7c reveal the complete absence of both RG and YB color vision with thresholds  
329 limited only by the gamut of the visual display employed in the CAD test. Despite making  
330 typical confusions expected for a rod monochromat<sup>9</sup> with the standard D-15 protocol, the rod  
331 monochromat was able to arrange the caps correctly when they were separated into the two  
332 subgroups with only one minor transposition (mixing caps 9 and 10 in the first test). Given  
333 that these caps generate almost equal rod photoreceptor signals, as shown in Figure 7d, this  
334 result is not unexpected. The results show that monotonic changes in rod photoreceptor  
335 signals, when the retina contains only functioning rods, can be used to complete the  
336 arrangement of D-15 caps without errors, but only when the ambiguity of equal rod signals is  
337 removed by separating the caps within the two subgroups.  
338 Systematic diseases and diseases of the retina can result in a reduction in luminance contrast  
339 and flicker sensitivity, in addition to loss of RG and / or YB color vision<sup>45,46</sup>. The D-15's

340 inability to isolate color signals and to quantify severity of RG and YB loss impact its  
341 usefulness as a test for use in occupational settings. However, in the clinic where one wishes  
342 to distinguish those with acquired visual loss that can affect chromatic sensitivity, but may  
343 not be specific to just color vision from those with normal, healthy vision, a test that requires  
344 the use of multiple visual signals to complete, such as the D-15, may prove to be sensitive  
345 and effective in achieving this aim.

## 346 **5. Conclusion**

347 When the D-15 protocol allows for up to two adjacent transpositions, 50% of color deficient  
348 subjects (approximately 54% of deuterans and 43% of protans), some with severe loss of RG  
349 color vision, pass the test. Given these large percentages of deuterans and protans who pass the  
350 D-15, the ability of the test to classify the type of color vision deficiency in anomalous  
351 trichromats is very poor. This test is also unfair to some of the subjects who fail. Many of  
352 those who pass the D-15 protocol have marked loss of RG color vision, whilst subjects with  
353 significantly less marked loss, fail.

354 In this study we demonstrate that neither RG nor YB color signals in isolation are sufficient  
355 to pass the D-15 test with no errors. The results also show that a subject can make use of  
356 monotonic changes in rod signals to arrange the caps in the correct sequence, but only in rod  
357 monochromats when rod signals do not interact with other cone signals.

358

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366

367 **Disclosures:**

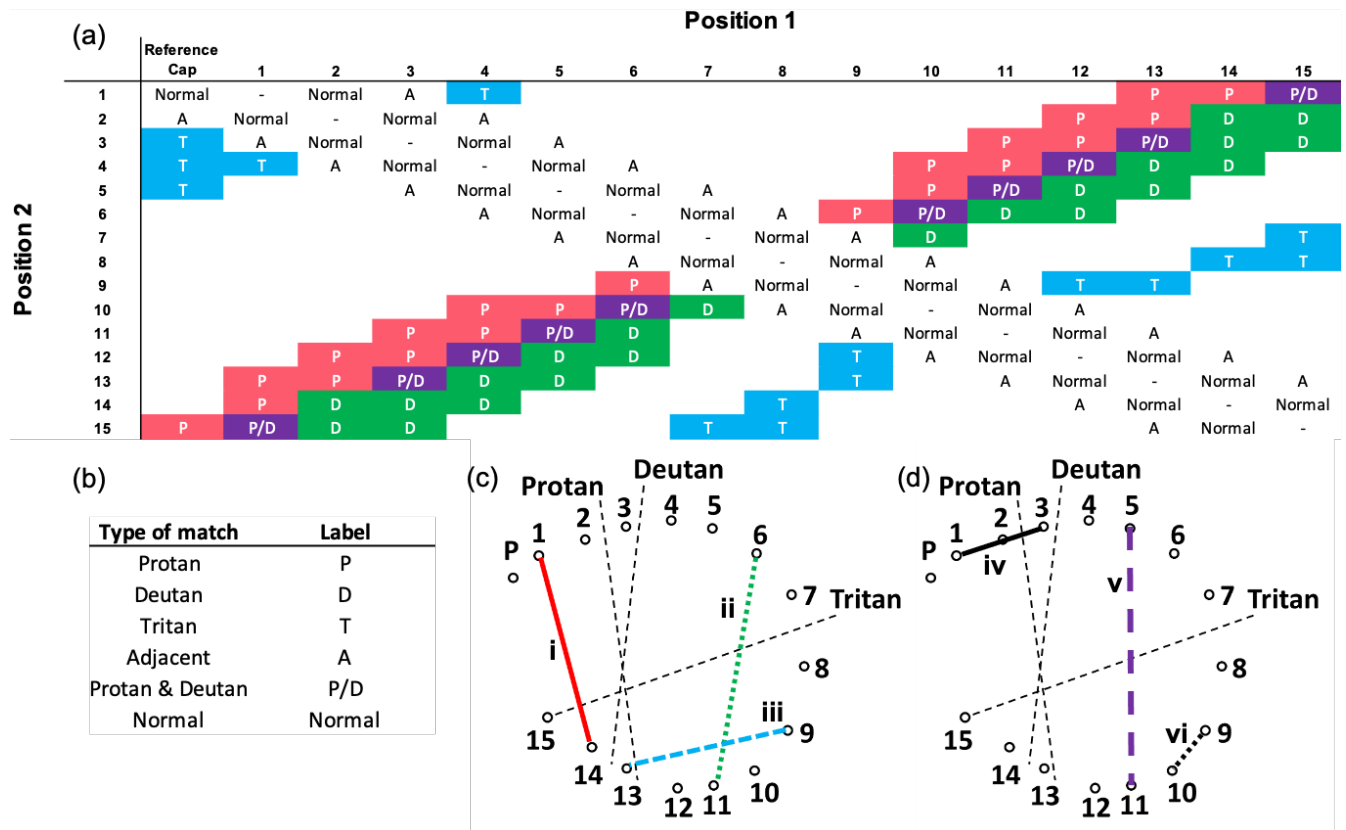
**Benjamin Evans,** City, University of London, None.

**Marisa Rodriguez-Carmona,** City, University of London, None.

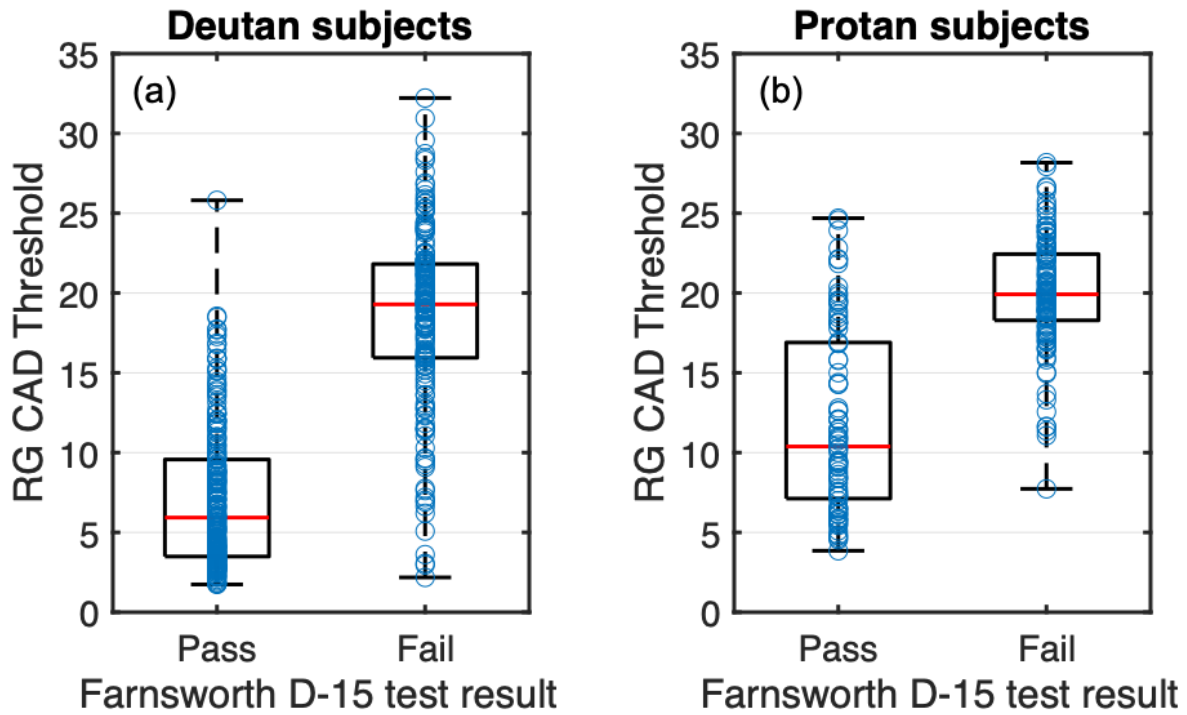
**John Barbur,** Employee of City, University of London. Company  
Director for COL Ltd. (A spin-out company set up by City,  
University of London to develop and market AVOT tests)

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373 Figure 1. Classification grid for the Farnsworth D-15 test employed in this study (a), the key  
 374 for the classification grid (b), and two D-15 results diagrams with example matches (c) and  
 375 (d). The common practice used in the majority of clinical and occupational environments  
 376 relies on ‘visual inspection’ and identification of adjacent transpositions and major crossings  
 377 on a D-15 results diagram. The classification grid shown in (a) is used in the color research  
 378 laboratory at City, University of London to make the process less subjective and open to  
 379 interpretation. The subject’s D-15 cap order yields 15 sets of sequential pairs and each pair  
 380 can be then be linked through the classification grid to one of six types of matches (b). The  
 381 overall D-15 classification is determined by the largest sum of errors (e.g., if an individual  
 382 makes 4 ‘protan’ crossings and 2 ‘deutan’ crossings, the D-15 classification would be  
 383 ‘protan’). In the event when an individual makes the same number of errors for two types of  
 384 error, the classification is ‘indeterminate’. Examples of the six match types are shown in the  
 385 D-15 results diagrams (c) and (d) for protan (i), deutan (ii), tritan (iii), adjacent transpositions  
 386 (iv), deutan and protan (v), and normal matches (vi). ‘Protan & deutan’ errors count as both a  
 387 protan and a deutan error.

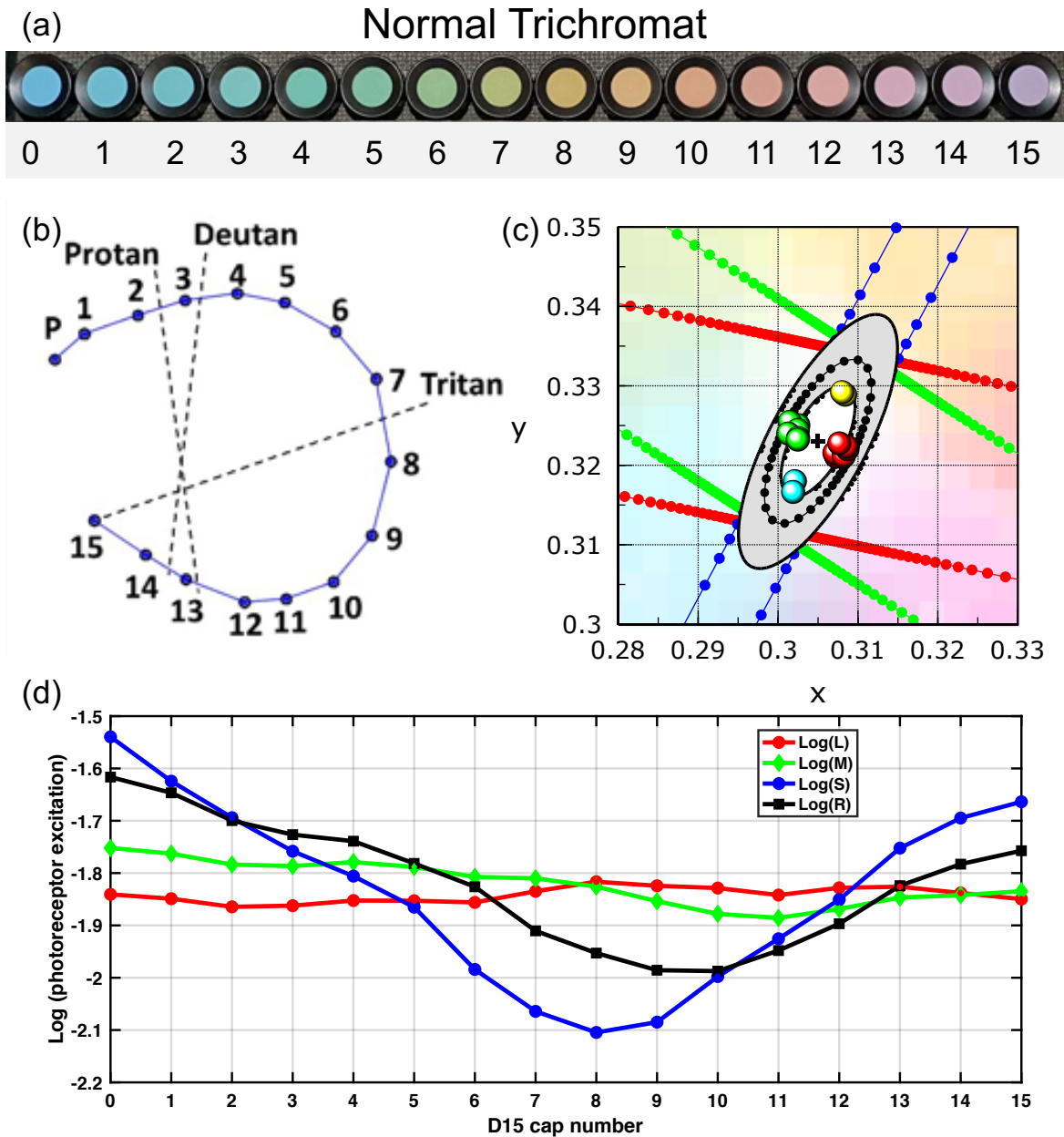


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390 Figure 2. The variability in RG CAD thresholds for subjects with congenital deutan  
 391 deficiency (a) and congenital protan deficiency (b) who pass or fail the Farnsworth D-15 test  
 392 when 0 major crossings and up to 2 adjacent transpositions are accepted as a pass. The results  
 393 are from 395 deutan and 205 protan subjects examined with the Farnsworth D-15, CAD and  
 394 Nagel anomaloscope. The results are shown using box plots where the median RG CAD  
 395 threshold (red line) and the interquartile range are shown for each plot.

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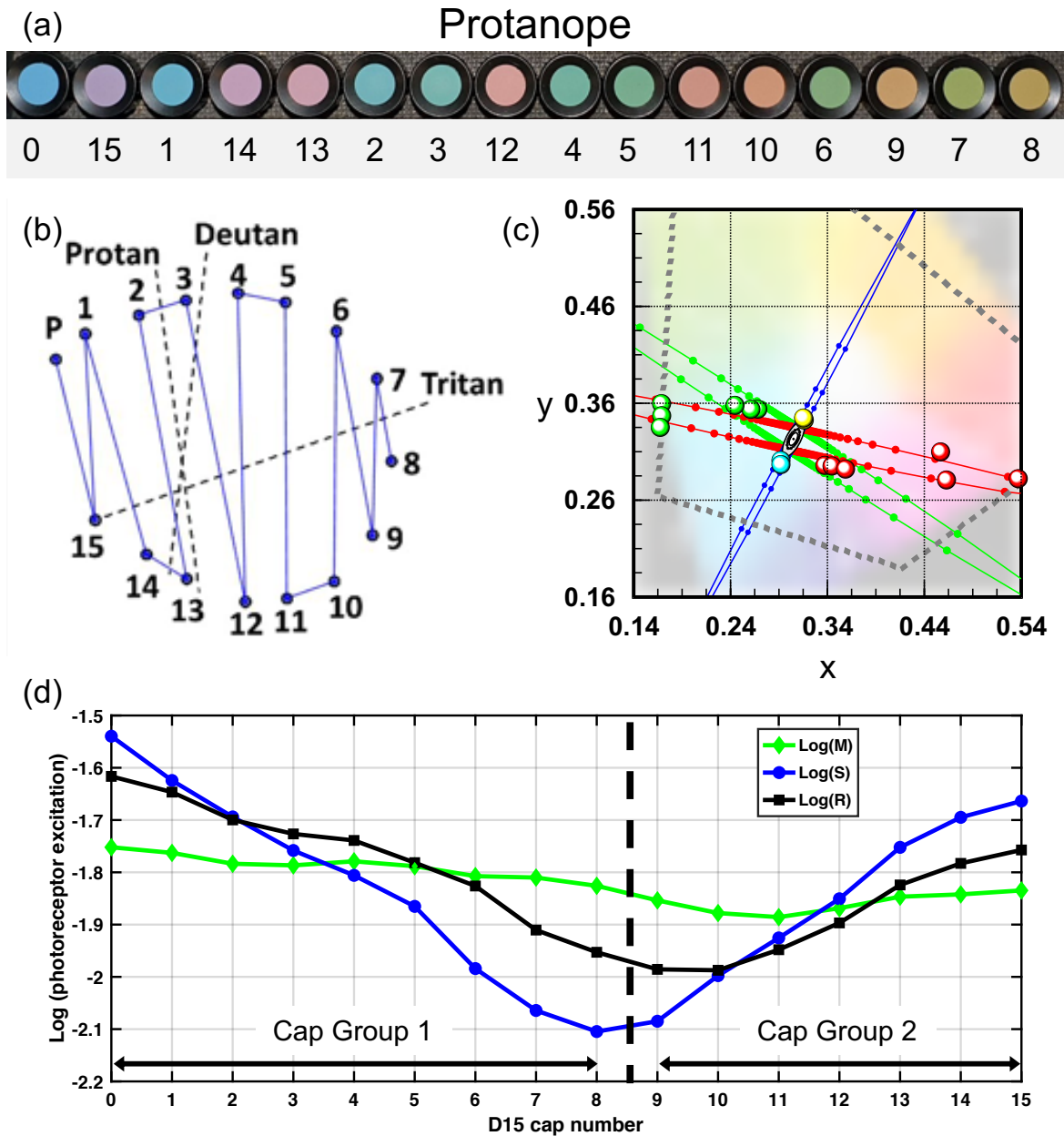


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399 Figure 3. Measured data and theoretical photoreceptor excitations for a normal trichromat.  
 400 Sections (a) and (b) show the recorded Farnsworth D-15 test results for a normal trichromat.  
 401 This individual's CAD test results are displayed in CIE 1931 color space (c). The normal  
 402 trichromat's CAD thresholds lie within the grey ellipse that indicates the normal range of  
 403 CAD thresholds expected for this subject's age. Section (d) shows the predicted  
 404 photoreceptor excitations for each of the Farnsworth D-15 caps when illuminated with a lamp  
 405 designed to approximate a D65 illuminant. These predictions were generated by measuring  
 406 the spectral radiance of each of the 16 caps when illuminated with the D65 illuminant.

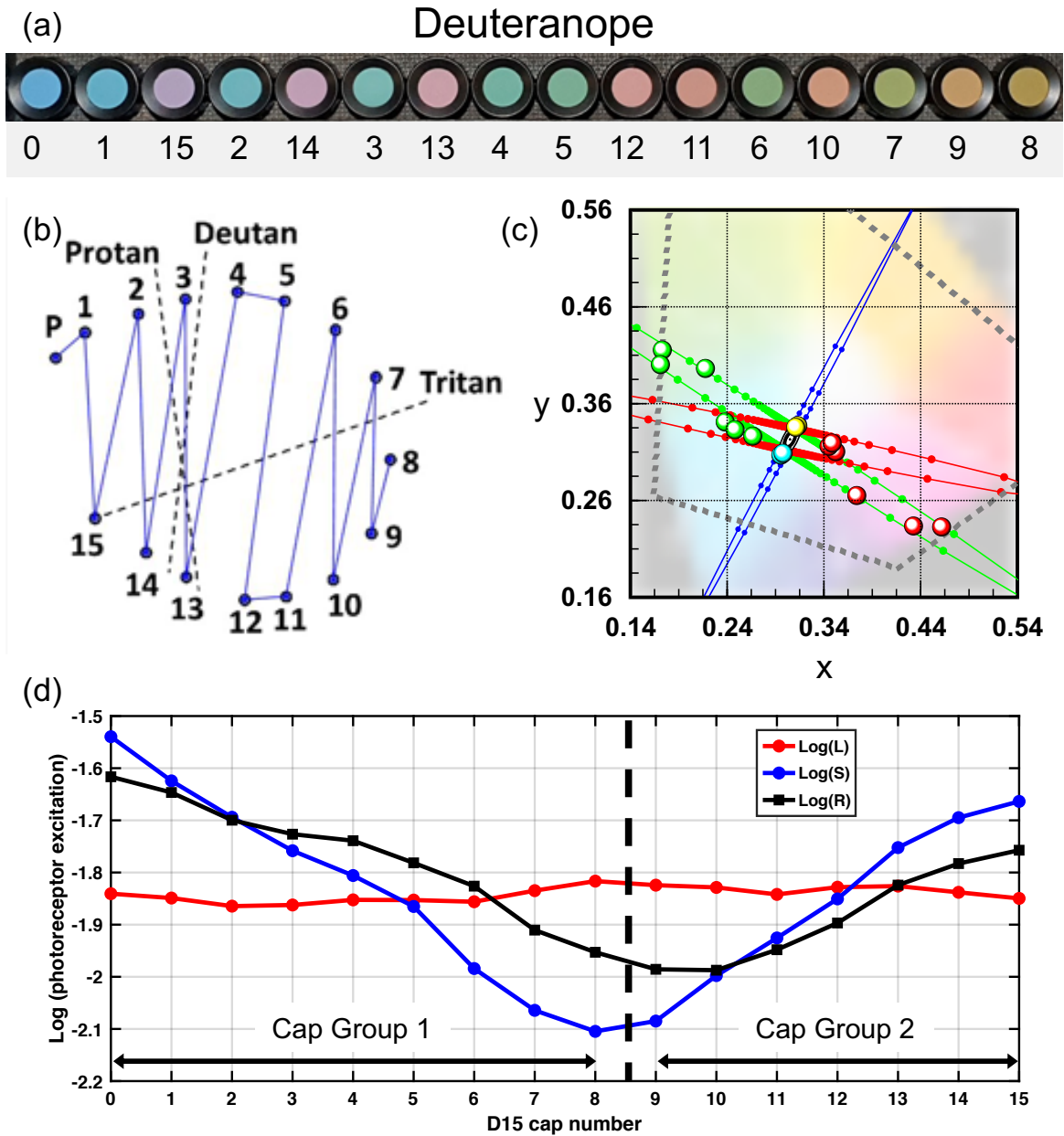
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Figure 4. Measured data and computed photoreceptor excitations expected for a protanope. Sections (a) and (b) show the recorded Farnsworth D-15 test results for an individual with protanopia. The patient's CAD test results are shown in section (c). Section (d) shows the predicted photoreceptor excitations for each of the Farnsworth D-15 caps when viewed by an individual with protanopia. When separated in to two groups, the protanope arranges all caps in the sequence recorded for normal trichromats, with no errors in each group.

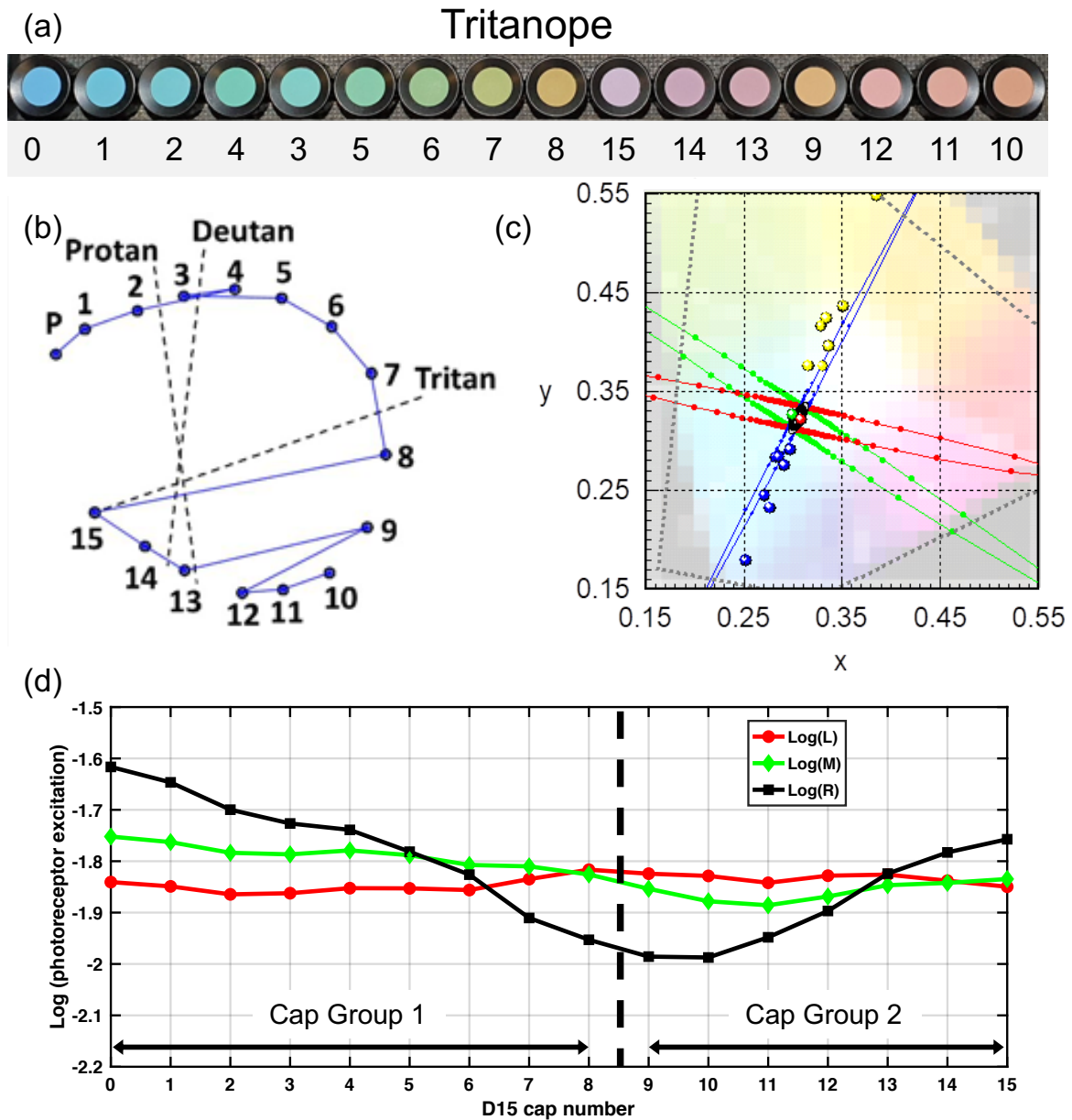


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418 Figure 5. Measured data and theoretical photoreceptor excitations for a deuteranope. Sections  
 419 (a) and (b) show the recorded Farnsworth D-15 test results for an individual with  
 420 deuteranopia. The patient's CAD test results are shown in section (c). Section (d) shows the  
 421 predicted photoreceptor excitations for each of the Farnsworth D-15 caps when viewed by an  
 422 individual with deuteranopia. When separated in to two groups, the deuteranope arranges all  
 423 caps in the sequence recorded for normal trichromats, with no errors in each group.

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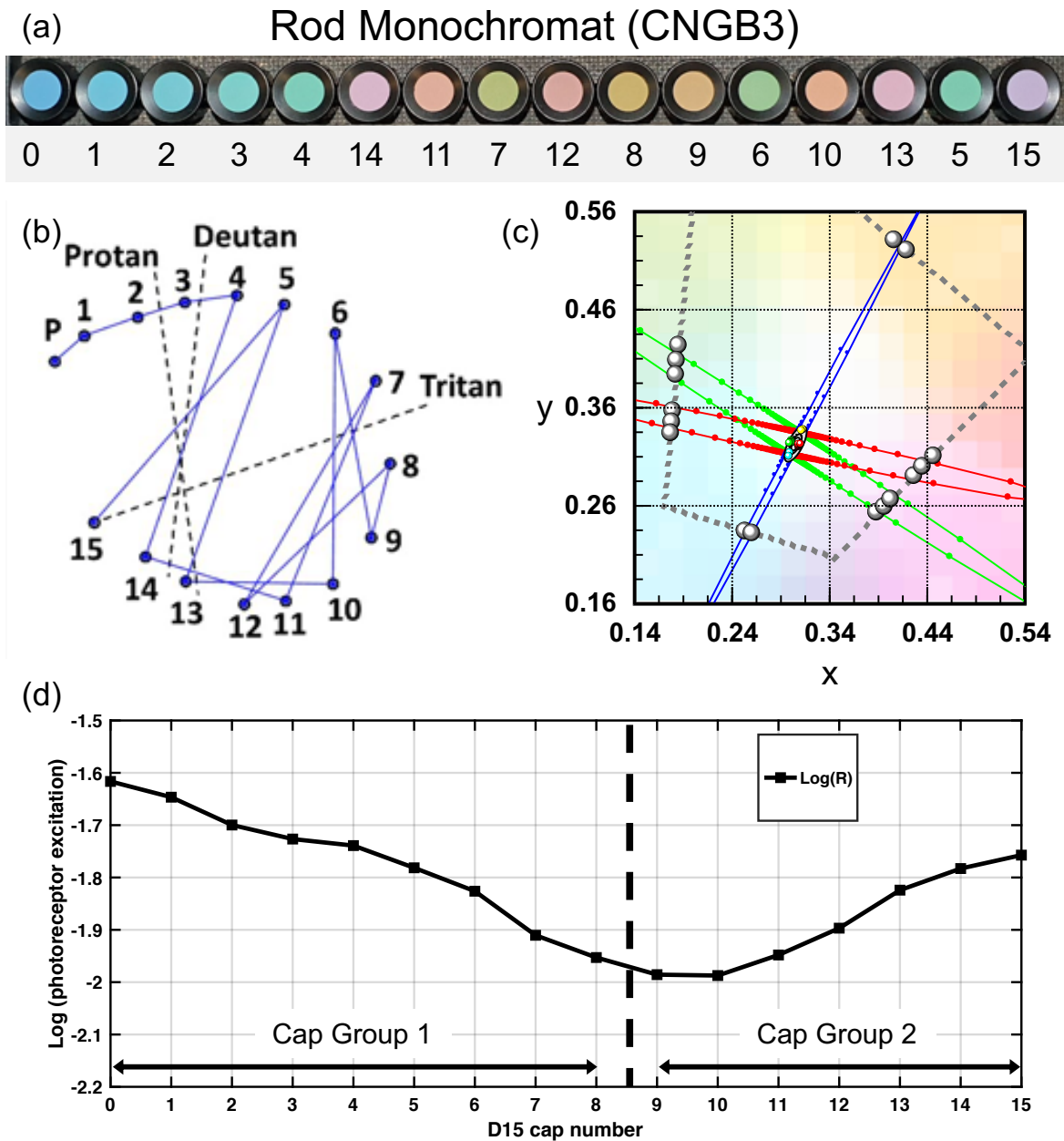


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427 Figure 6. Measured data and theoretical photoreceptor excitations for a tritanope. Sections (a)  
 428 and (b) show the recorded Farnsworth D-15 test results for an individual with tritanopia. The  
 429 patient's CAD test results are shown in section (c). Section (d) shows the predicted  
 430 photoreceptor excitations for each of the Farnsworth D-15 caps when viewed by an  
 431 individual with tritanopia. When separated in to two groups, the tritanope is unable to arrange  
 432 all caps in the sequence recorded for normal trichromats, making multiple errors in each  
 433 group.

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437 Figure 7. Measured data and theoretical photoreceptor excitations for a rod monochromat  
 438 (CNGB3). Sections (a) and (b) show the recorded Farnsworth D-15 test results for an  
 439 individual with rod monochromacy. The patient's CAD test results are shown in section (c).  
 440 Section (d) shows the predicted photoreceptor excitations for each of the Farnsworth D-15  
 441 caps when viewed by an individual with rod monochromacy. When separated in to two  
 442 groups, the rod monochromat arranges the caps almost completely correctly, only making one  
 443 minor transposition (cap 9 and 10 during the first test and interchanging the order of these  
 444 two caps in repeated tests).

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446 **Outcome of the Farnsworth D-15 test**

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Type of colour deficiency	Number of subjects	Percentage of subjects who pass using different pass criteria	
		No adjacent transpositions are accepted	Up to two adjacent transpositions are accepted
(a)			
Deuteranopia	117	1.7	3.4
Deuteranomalous trichromatism	278	65.5	75.5
Protanopia	89	3.4	9.0
Protanomalous trichromatism	116	59.5	69.0
(b)			
Anomalous trichromats	394	63.7	73.6
Dichromats	206	2.4	5.8
(c)			
Deutan	395	46.6	54.2
Protan	205	35.1	42.9

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Table 1. Farnsworth D-15 pass/fail statistics for a sample of 600 subjects with congenital color vision deficiency, when 0 major crossings and 0 adjacent transpositions, and 0 major crossings and up to 2 adjacent transpositions are accepted as a pass. One normal trichromat (~1%) made adjacent transpositions and a pass protocol that allowed subjects to make 0 major crossings and up to 2 adjacent transpositions was the most stringent protocol needed to pass all normal subjects (N=74) investigated.

456 **Classification outcome of the Farnsworth D-15 test**

Type of colour deficiency	Number of subjects	Classification made by the Farnsworth D-15 (%)				
		Normal	Deutan	Protan	Tritan	Indeterminate
(a)						
Deuteranopia	117	1.7	94.9	0.0	0.0	3.4
Deuteranomalous trichromatism	278	65.4	19.8	0.0	0.4	14.4
Protanopia	89	3.4	4.5	80.9	0.0	11.2
Protanomalous trichromatism	116	59.5	3.4	21.6	0.0	15.5
(b)						
Deuteranopia	113	0.0	98.2	0.0	0.0	1.8
Deuteranomalous trichromatism	68	0.0	80.9	0.0	1.5	17.6
Protanopia	81	0.0	4.9	88.9	0.0	6.2
Protanomalous trichromatism	36	0.0	11.1	69.5	0.0	19.4

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458 Table 2. The percentage of subjects that fall into each Farnsworth D-15 classification  
 459 category for all subjects (a) and for subjects that fail the D-15, when up to two adjacent  
 460 transpositions are accepted (b). The classification made by the Farnsworth D-15 was  
 461 determined using the classification grid shown in Figure 1a and the type of color vision  
 462 deficiency was determined using the Nagel anomaloscope and the CAD test. There was 100%  
 463 agreement between the CAD test and Nagel anomaloscope.

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465 **References**

- 466 1. Rodríguez-Carmona M, Evans BEW, Barbur JL. Color Vision Assessment: 2. Color  
467 assessment outcomes using single and multi-test protocols. *Color Res Appl.*  
468 2020;Submitted.
- 469 2. Barbur JL, Rodríguez-Carmona M, Evans BEW. Color Vision Assessment: 3. An  
470 efficient two-step color assessment protocol. *Color Res Appl.* 2020;Submitted.
- 471 3. Farnsworth D. *Farnsworth Dichotomous Test for Color Blindness*. San Antonio, TX,  
472 US: Psychological Corporation; 1947.
- 473 4. Almustanyir A, Hovis J, Glaholt MG. Predicting the Farnsworth–Munsell D15 and  
474 Holmes–Wright-A lantern outcomes with computer-based color vision tests. *J Opt Soc*  
475 *Am A.* 2020;37(4):A1. doi:10.1364/JOSAA.381305
- 476 5. Dain SJ. Clinical colour vision tests. *Clin Exp Optom.* 2004;276-293.
- 477 6. Margrain TH, Birch J, Owen CG. Colour vision requirements of firefighters. *Occup*  
478 *Med (Chic Ill).* 1996;46(2):114-124. doi:10.1093/occmed/46.2.114
- 479 7. Dain SJ, Casolin A, Long J, Hilmi MR. Color vision and the railways: Part 1. The  
480 railway LED lantern test. *Optom Vis Sci.* 2015;92(2):138-146.  
481 doi:10.1097/OPX.0000000000000460
- 482 8. Dain SJ, Wood JM, Atchison DA. Sunglasses, traffic signals, and color vision  
483 deficiencies. *Optom Vis Sci.* 2009;86(4):e296-e305.  
484 doi:10.1097/OPX.0b013e318199d1da
- 485 9. Birch J. *Diagnosis of Defective Colour Vision*. Oxford: Butterworth-Heinemann; 2001.
- 486 10. Foutch BK, Stringham JM, Lakshminarayanan V. A new quantitative technique for  
487 grading Farnsworth D-15 color panel tests. *J Mod Opt.* 2011;58(19-20):1755-1763.  
488 doi:10.1080/09500340.2011.573881
- 489 11. Bowman KJ. A Method for Quantitative Scoring of the Farnsworth Panel D-15. *Acta*  
490 *Ophthalmol.* 1982;60(6):907-916. doi:10.1111/j.1755-3768.1982.tb00621.x
- 491 12. Atchison DA, Bowman KJ, Vingrys AJ. Quantitative scoring of panel tests for  
492 assessment of colour vision in age related maculopathy. *Clin Exp Optom.*  
493 1991;74(1):6-10. doi:10.1111/j.1444-0938.1991.tb04600.x
- 494 13. Vingrys AJ, King-Smith PE. A quantitative scoring technique for panel tests of color  
495 vision. *Investig Ophthalmol Vis Sci.* 1988;29(1):50-63.
- 496 14. Almustanyir A, Hovis J. Trichromatic And Dichromatic Colorimetric Analyses Of The  
497 Farnsworth-Munsell D-15 Color Vision Test. In: *Proceedings of the 29th Quadrennial*  
498 *Session of the CIE*. International Commission on Illumination, CIE; 2019:909-916.  
499 doi:10.25039/x46.2019.PO012
- 500 15. Pacheco-Cutillas M, Edgar DF, Sahraie A. Acquired colour vision defects in  
501 glaucoma---their detection and clinical significance. *Br J Ophthalmol.*  
502 1999;83(12):1396-1402. doi:10.1136/bjo.83.12.1396
- 503 16. Birch J. Pass rates for the Farnsworth D15 colour vision test. *Ophthalmic Physiol Opt.*  
504 2008;28(3):259-264. doi:10.1111/j.1475-1313.2008.00566.x

- 505 17. Birch J, Chisholm CM. Occupational colour vision requirements for police officers.  
506 *Ophthalmic Physiol Opt.* 2008;28(6):524-531. doi:10.1111/j.1475-1313.2008.00605.x
- 507 18. Pokorny J, Collins B, Howett G, et al. Procedures for Testing Color Vision: Report of  
508 working group 41. *Natl Res Counc.* 1981. doi:10.1097/00006324-198211000-00014
- 509 19. Atchison DA, Pedersen CA, Dain SJ, Wood JM. Traffic Signal Color Recognition Is a  
510 Problem for Both Protan and Deutan Color-Vision Deficients. *Hum Factors.*  
511 2003;45(3):495-503. doi:10.1518/hfes.45.3.495.27247
- 512 20. Barbur JL, Holliday IE, Ruddock KH. The spatial and temporal organisation of motion  
513 perception units in human vision. *Acta Psychol (Amst).* 1981;48(1-3):35-47.
- 514 21. Barbur JL, Ruddock KH. Spatial characteristics of movement detection mechanisms in  
515 human vision. II. Chromatic stimuli. *Biol Cybern.* 1980;37(2):93-98.
- 516 22. Barbur JL, Harlow AJ, Plant GT. Insights into the Different Exploits of Colour in the  
517 Visual Cortex. *Proc R Soc B Biol Sci.* 1994;258(1353):327-334.  
518 doi:10.1098/rspb.1994.0181
- 519 23. Barbur JL. "Double-blindsight" revealed through the processing of color and  
520 luminance contrast defined motion signals. *Prog Brain Res.* 2004;144:243-259.  
521 doi:10.1016/S0079-6123(03)14417-2
- 522 24. Barbur JL, Rodriguez-Carmona M. Colour vision requirements in visually demanding  
523 occupations. *Br Med Bull.* 2017;122(1):51-77. doi:10.1093/bmb/ldx007
- 524 25. Rodriguez-Carmona M, O'Neill-Biba M, Barbur JL. Assessing the severity of color  
525 vision loss with implications for aviation and other occupational environments. *Aviat*  
526 *Sp Environ Med.* 2012;83(1):19-29. doi:10.3357/ASEM.3111.2012
- 527 26. Jägle H, Pirzer M, Sharpe LT. The Nagel anomaloscope: its calibration and  
528 recommendations for diagnosis and research. *Graefe's Arch Clin Exp Ophthalmol.*  
529 2005;243(1):26-32. doi:10.1007/s00417-004-0893-z
- 530 27. Birch J. Failure of concordance of the Farnsworth D15 test and the Nagel  
531 anomaloscope matching range in anomalous trichromatism. *Vis Neurosci.*  
532 2008;25(3):451-453. doi:10.1017/S0952523808080231
- 533 28. Barbur JL, Rodriguez-Carmona M, Harlow JA, Mancuso K, Neitz J, Neitz M. A study  
534 of unusual Rayleigh matches in deutan deficiency. *Vis Neurosci.* 2008;25(3):507-516.  
535 doi:10.1017/S0952523808080619
- 536 29. Jägle H, Sharpe LT. The Nagel anomaloscope : its calibration and recommendations  
537 for diagnosis and research. 2005:26-32. doi:10.1007/s00417-004-0893-z
- 538 30. Wright WD. *Researches on Normal & Defective Colour Vision.* Kimpton; 1946.
- 539 31. Dain SJ, Atchison DA, Hovis JK. Limitations and Precautions in the Use of the  
540 Farnsworth-Munsell Dichotomous D-15 Test. *Optom Vis Sci.* 2019;96(9):695-705.  
541 doi:10.1097/opx.0000000000001420
- 542 32. Ng JS, Liem SC. Can the farnsworth D15 color vision test be defeated through  
543 practice? *Optom Vis Sci.* 2018;95(5):452-456. doi:10.1097/OPX.0000000000001218
- 544 33. Ng JS, Morton WA. Case Report: Invalidation of the Farnsworth D15 Test in  
545 Dichromacy Secondary to Practice. *Optom Vis Sci.* 2018;95(3):272-274.

- 546 doi:10.1097/OPX.0000000000001184
- 547 34. Cole BL. Assessment of inherited colour vision defects in clinical practice. *Clin Exp*  
548 *Optom.* 2007;90(3):157-175. doi:10.1111/j.1444-0938.2007.00135.x
- 549 35. DeMarco P, Pokorny J, Smith VC. Full-spectrum cone sensitivity functions for X-  
550 chromosome-linked anomalous trichromats. *J Opt Soc Am A.* 1992;9(9):1465.  
551 doi:10.1364/JOSAA.9.001465
- 552 36. Wyszecki G, Stiles WS. *Color Science: Concepts and Methods Quantitative Data and*  
553 *Formulae.* Vol 8. 2nd Ed. Wiley New York; 1982.
- 554 37. Dain SJ, Adams AJ. Comparison of the standard and Adams desaturated D-15 tests  
555 with congenital colour vision deficiencies. *Ophthalmic Physiol Opt.* 1990;10(1):40-45.  
556 doi:10.1111/j.1475-1313.1990.tb01105.x
- 557 38. Dain SJ, Ling BY. Cognitive abilities of children on a gray seriation test. *Optom Vis*  
558 *Sci.* 2009;86(6):E701-E707. doi:10.1097/OPX.0b013e3181a59d46
- 559 39. Cranwell MB, Pearce B, Loveridge C, Hurlbert AC. Performance on the Farnsworth-  
560 Munsell 100-hue test is significantly related to nonverbal IQ. *Investig Ophthalmol Vis*  
561 *Sci.* 2015;56(5):3171-3178. doi:10.1167/iovs.14-16094
- 562 40. Allen AE, Martial FP, Lucas RJ. Form vision from melanopsin in humans. *Nat*  
563 *Commun.* 2019;10(1):1-10. doi:10.1038/s41467-019-10113-3
- 564 41. Patterson SS, Kuchenbecker JA, Anderson JR, Neitz M, Neitz J. A Color Vision  
565 Circuit for Non-Image-Forming Vision in the Primate Retina. *Curr Biol.*  
566 2020;30(7):1269-1274.e2. doi:10.1016/j.cub.2020.01.040
- 567 42. Markwell EL, Feigl B, Zele AJ. Intrinsically photosensitive melanopsin retinal  
568 ganglion cell contributions to the pupillary light reflex and circadian rhythm. *Clin Exp*  
569 *Optom.* 2010;93(3):137-149. doi:10.1111/j.1444-0938.2010.00479.x
- 570 43. Cao D, Chang A, Gai S. Evidence for an impact of melanopsin activation on unique  
571 white perception. *J Opt Soc Am A.* 2018;35(4):B287. doi:10.1364/JOSAA.35.00B287
- 572 44. Schmidt TM, Do MTH, Dacey D, Lucas R, Hattar S, Matynia A. Melanopsin-positive  
573 intrinsically photosensitive retinal ganglion cells: From form to function. *J Neurosci.*  
574 2011;31(45):16094-16101. doi:10.1523/JNEUROSCI.4132-11.2011
- 575 45. Bi W, Gillespie-Gallery H, Binns A, Barbur JL. Flicker sensitivity in normal aging—  
576 monocular tests of retinal function at photopic and mesopic light levels. *Investig*  
577 *Ophthalmol Vis Sci.* 2016;57(2):387-395. doi:10.1167/iovs.15-16481
- 578 46. Rauscher FG, Chisholm CM, Edgar DF, Barbur JL. Assessment of novel binocular  
579 colour, motion and contrast tests in glaucoma. *Cell Tissue Res.* 2013;353(2):297-310.  
580 doi:10.1007/s00441-013-1675-x

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593 **John Barbur** combines fundamental vision science with applied and clinical research. His  
594 main interests include mesopic vision, pupil responses and eye movements, blindsight, spatial  
595 and chromatic vision, scattered light and the development of novel techniques and  
596 instrumentation to study vision, both in the lab and in the clinic. Work on camouflage led to  
597 insights into the processing of luminance and colour signals, the development of the Colour  
598 Assessment and Diagnosis (CAD) test and more recently, the Colour Vision Screener (CVS)  
599 test. These and other Advanced Vision and Optometric Tests (AVOT) were developed over  
600 several years and found important applications in both clinical work and in visually-  
601 demanding occupations.