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

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Abstract:

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

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

1. Introduction

This is the first in a series of three papers which examined common color assessment tests employed in the clinic to detect early changes in chromatic sensitivity and also in occupations to screen for congenital and / or acquired loss of color vision in order to relate test outcomes to class and severity of color vision loss. This paper evaluates the performance of the Farnsworth D-15 test (D-15) at screening for and classifying color vision deficiency, in addition to appraising the residual signals that enable subjects with reduced chromatic sensitivity to successfully arrange the caps. The second paper[1] evaluates the statistical outcomes of commonly used color assessment tests and examines the efficiency of frequently used single- and multi-test protocols. The third paper[2] assesses the fundamental limits of what one can achieve in color vision assessment and describes a new test that approaches this limit.

Following its introduction over 70 years ago[3] the D-15 continues to be used to screen for individuals with reduced chromatic sensitivity in occupational and clinical environments[4–8]. The standard D-15 consists of 16 Munsell hues, mounted in circular casings or 'caps', of approximately 13mm in diameter. Participants are provided with a fixed reference or pilot cap and are asked to select and arrange the remaining caps, one by one, in each instance selecting the cap that appears to be least-different perceptually to the most recently selected cap[9].

Various methods for establishing error scores have been described[10–13] and in a recent study, the type and number of errors subjects make have even been related with some success to the colorimetric characteristics of the caps[14]. In spite of such efforts, the preferred method of interpreting the results of the D-15 in most clinical settings is to plot the subject's arranged sequence on a circular diagram[15,16]. The circular diagram plays a large role in the ease of administration and interpretation of the results. Errors made on the D-15 are classified, based 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[17] to allowing up to 2 major isochromatic
68 crossings[18]; 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[8,9,19], 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[20,21].
76 Further studies on camouflage revealed new ways to isolate the use of color signals without
77 affecting significantly the sensitivity of chromatic mechanisms[22,23]. 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[24] that
80 are approximately linearly proportional to the cone contrasts generated by the colored
81 stimulus[25]. 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[9,26]. Although the disagreement between the anomaloscope matching range and the
84 outcome of the D-15 test has been previously documented by Birch[27], 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[28,29], the relationship between the parameters of the match and the subject's overall
88 chromatic sensitivity is known to be generally poor[30].
89 The limitations of the D-15, including the potential effects on the D-15 from variation in
90 illuminants, have recently been highlighted[31] and the impact that practice can have on the

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

2. Methods

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

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

CIE 1931 chromaticity of 0.306, 0.324. This corresponds approximately to an illuminance level of 293 lm/m^2.

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

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

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

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

140 the Smith and Pokorny cone fundaments[35] to estimate cap-specific cone excitations. The
141 spectral luminous efficiency function, V'(λ), was used to calculate the corresponding rod
142 photoreceptor excitations[36].
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

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

3. Results

When no crossings and no adjacent transpositions are accepted, 99% of normal trichromats, 66% of deuteranomalous trichromats, 60% of protanomalous trichromats, 2% of deuteranopes and 3% of protanopes pass the D-15. When no crossings and up to two adjacent transpositions are accepted, 100% of normal trichromats pass the D-15. The percentage of subjects with congenital color vision deficiency who pass the D-15 are shown in Table 1a. When up to two adjacent transpositions are accepted, 76% of deuteranomalous trichromats, 69% of protanomalous trichromats, 3% of deuteranopes and 9% of protanopes pass the D-15. Approximately 74% of anomalous trichromats in this cohort pass, whereas only ~6% of dichromats pass (Table 1b), and 54% of deutans pass compared to 43% of protans (Table 1c). There was 100% agreement between the classification made by the CAD test and the Nagel anomaloscope for all subjects in this study. The classification made by the D-15 in all subjects and in those that fail the D-15, when up to two adjacent transpositions are accepted, is shown in Table 2a and Table 2b, respectively. For all subjects the D-15 correctly classifies 94.9% of deuteranopes, 80.9% of protanopes, and 19.8% and 21.6% of deuteranomalous and protanomalous trichromats, respectively. The classification made by the D-15 improves if one only considers those who fail the D-15, when up to two adjacent transpositions are accepted, with 98.2%, 88.9%, 80.9%, and 69.5% of deuteranopes, protanopes, deuteranomalous trichromats, and protanomalous trichromats respectively being classified correctly.

All subjects within the cohort had YB CAD thresholds within the normal range for their age. The distributions of RG CAD thresholds in deutans and protans who pass and fail the D-15 are shown in Figure 2. The median RG CAD thresholds for deutans that pass the D-15 was 5.93 RG CAD units and 10.38 RG CAD units for protans. One CAD unit describes the median RG or YB threshold color signal strengths measured in 330 heathy, young, normal trichromats[24]. Only 50% of normal trichromats have thresholds less than one CAD unit. The maximum RG CAD threshold for those who passed the D-15, when up to two adjacent transpositions were accepted, was 25.81 for deutans and 24.69 RG CAD units for protans. The predicted photoreceptor excitations generated by the D-15 caps are shown in Figure 3d. When two protanopes and two deuteranopes completed the D-15 under the standard protocol their results produced typical error patterns, with participants making multiple major iso-chromatic crossings (Figure 4b and Figure 5b). When the caps were separated into two subgroups, both protanopes and deuteranopes were able to arrange the caps within each subgroup with no errors. When a tritanope completed the same protocol, they were unable to arrange the caps correctly under standard conditions. This was also the case when presented with each of the two subgroups (Figure 6b).

Not unexpectedly, a rod monochromat (CNGB3) made several errors on the D-15 test under normal conditions (Figure 7b). When presented with each of the two subgroups, the rod monochromat was able to arrange the caps almost completely correctly, only making one minor transposition (cap 9 and 10 during the first test and interchanging the order of these two caps in repeated tests). These caps have approximately the same rod excitation, see Figure 7d.

4. Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

not unexpected; the diminished or even absent RG color signal differences that prevent typical protan and deutan confusions, particularly major crossings, are no longer possible and caps with equal S-cone excitation are not available within either of the two cap subgroups. The results in the tritanope (Figure 6) suggest strongly that normal RG color signals are not sufficient to pass the D-15 test with no errors, since the tritanope makes multiple errors when presented with the full set of caps and also makes errors when presented separately with each of the two subgroups. The rod monochromat, on the other hand, can only rely on monotonic changes in rod signals which can be used effectively within each subgroup to arrange the caps in the correct sequence. The tritanope makes multiple errors within each subgroup, in spite of normal rod function. An interesting consequence of this finding is that either the presence of normal RG color signals or simply the interaction between M, L and rod signals reduces the effectiveness of monotonic rod signal changes to carry out the test.

The results obtained in the rod monochromat merit further discussion. The results shown in Figure 7c reveal the complete absence of both RG and YB color vision with thresholds limited only by the gamut of the visual display employed in the CAD test. Despite making typical confusions expected for a rod monochromat[9] with the standard D-15 protocol, the rod monochromat was able to arrange the caps correctly when they were separated into the two subgroups with only one minor transposition (mixing caps 9 and 10 in the first test). Given that these caps generate almost equal rod photoreceptor signals, as shown in Figure 7d, this result is not unexpected. The results show that monotonic changes in rod photoreceptor signals, when the retina contains only functioning rods, can be used to complete the arrangement of D-15 caps without errors, but only when the ambiguity of equal rod signals is removed by separating the caps within the two subgroups.

Systematic diseases and diseases of the retina can result in a reduction in luminance contrast and flicker sensitivity, in addition to loss of RG and / or YB color vision[45,46]. The D-15's

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

5. Conclusion

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

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

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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)

Figures & tables

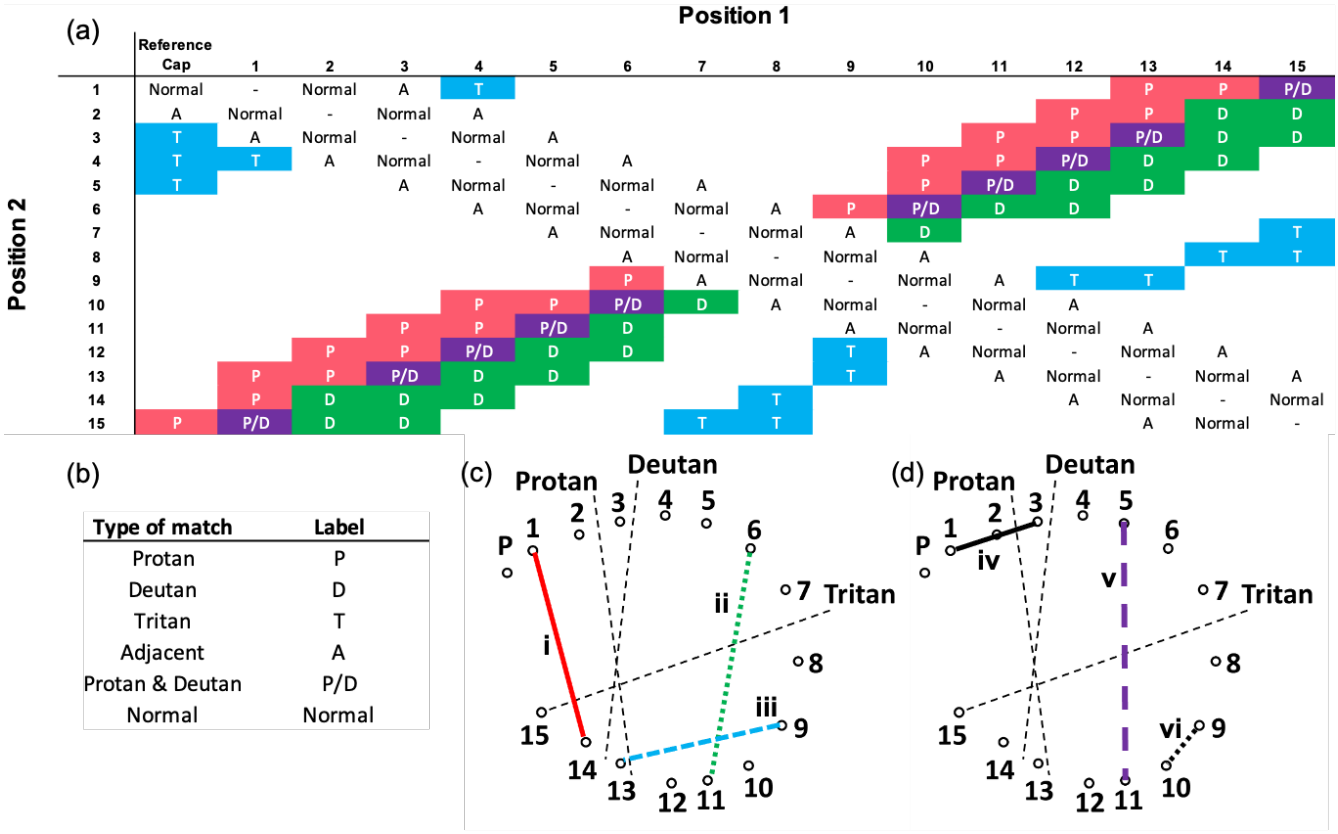

Figure 1. Classification grid for the Farnsworth D-15 test employed in this study (a), the key for the classification grid (b), and two D-15 results diagrams with example matches (c) and (d). The common practice used in the majority of clinical and occupational environments relies on 'visual inspection'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

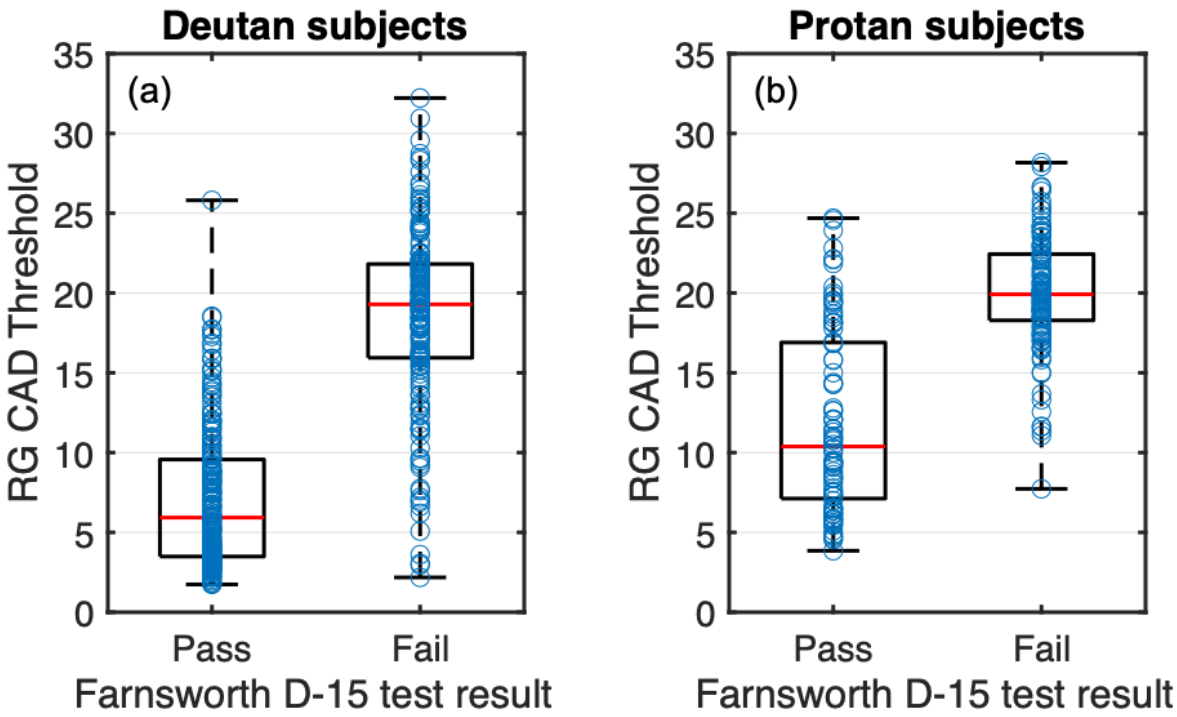

Figure 2. The variability in RG CAD thresholds for subjects with congenital deutan deficiency (a) and congenital protan deficiency (b) who pass or fail the Farnsworth D-15 test when 0 major crossings and up to 2 adjacent transpositions are accepted as a pass. The results are from 395 deutan and 205 protan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

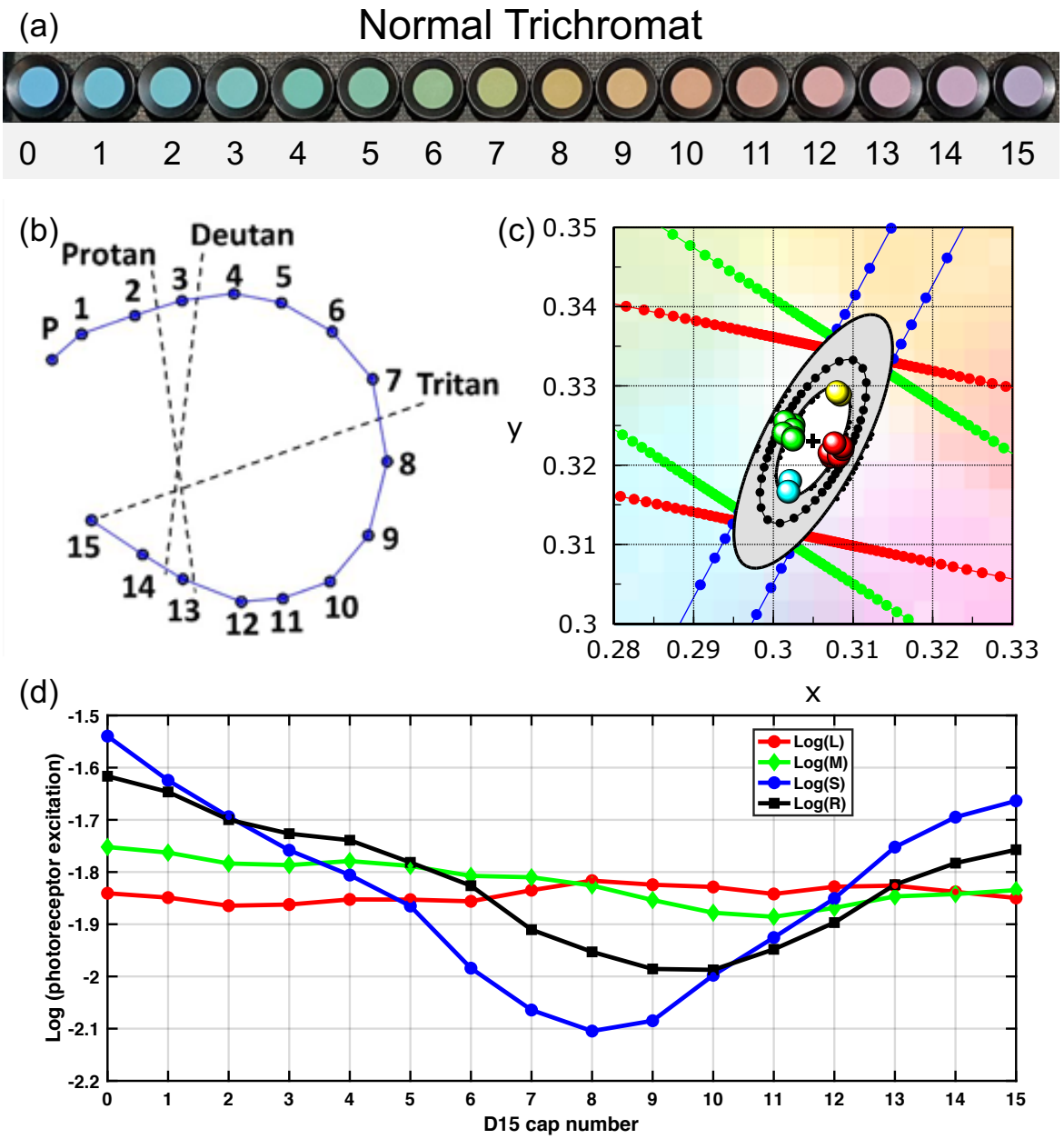

Figure 3. Measured data and theoretical photoreceptor excitations for a normal trichromat. Sections (a) and (b) show the recorded Farnsworth D-15 test results for a normal trichromat. This individual's CAD test results are displayed in CIE 1931 color space (c). The normal trichromat's CAD thresholds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

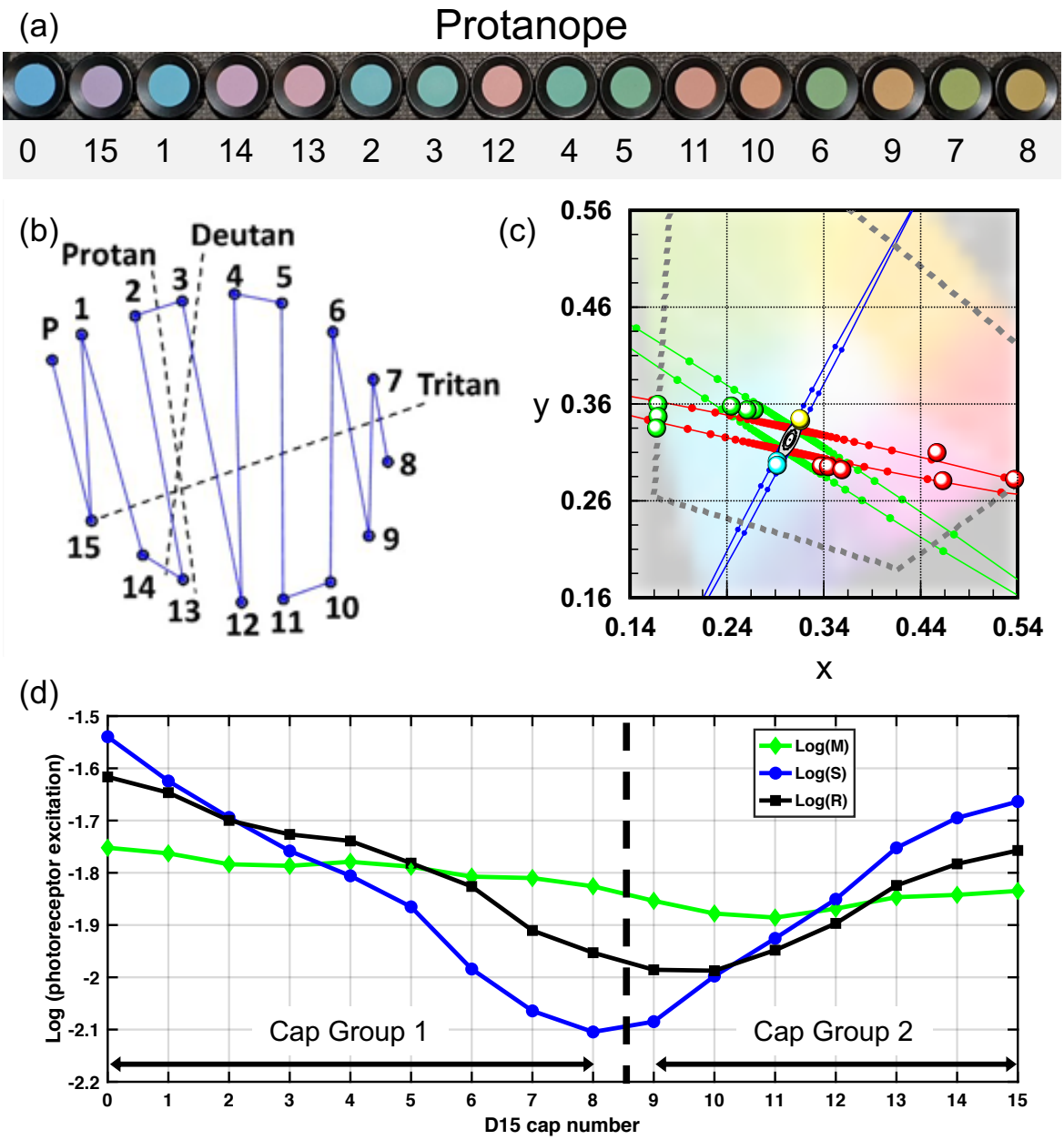

Figure 4. Measured data and computed photoreceptor excitations expected for a protanope. Sections (a) and (b) show the recorded Farnsworth D-15 test results for an individual with protanopia. The patient's CAD test results are shown in section (c). Section (d) shows the predicted photoreceptor excitations 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.

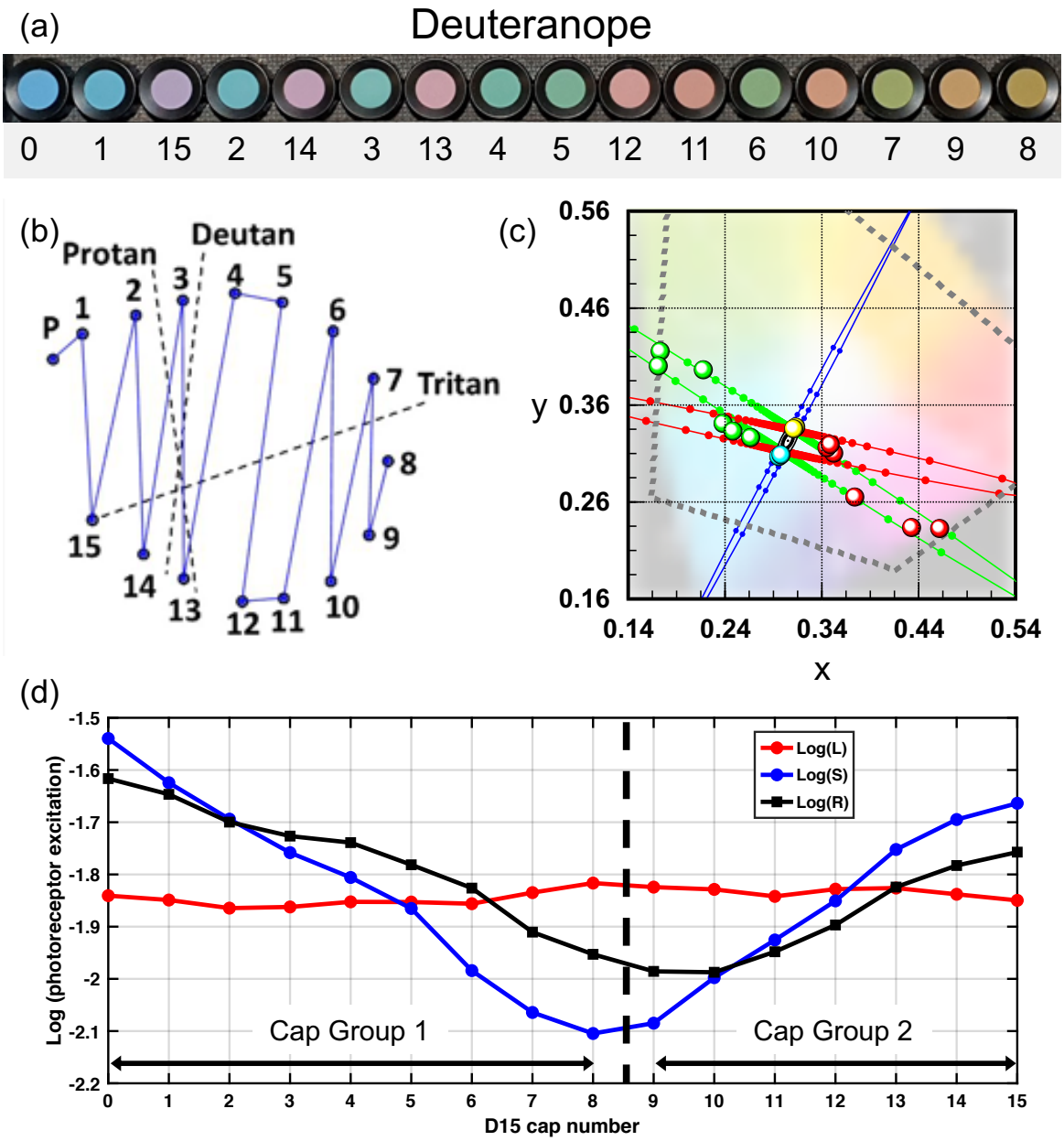

Figure 5. Measured data and theoretical photoreceptor excitations for a deuteranope. Sections (a) and (b) show the recorded Farnsworth D-15 test results for an individual with deuteranopia. The patient's CAD test results are shown in section (c). Section (d) shows the predicted photoreceptor excitations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

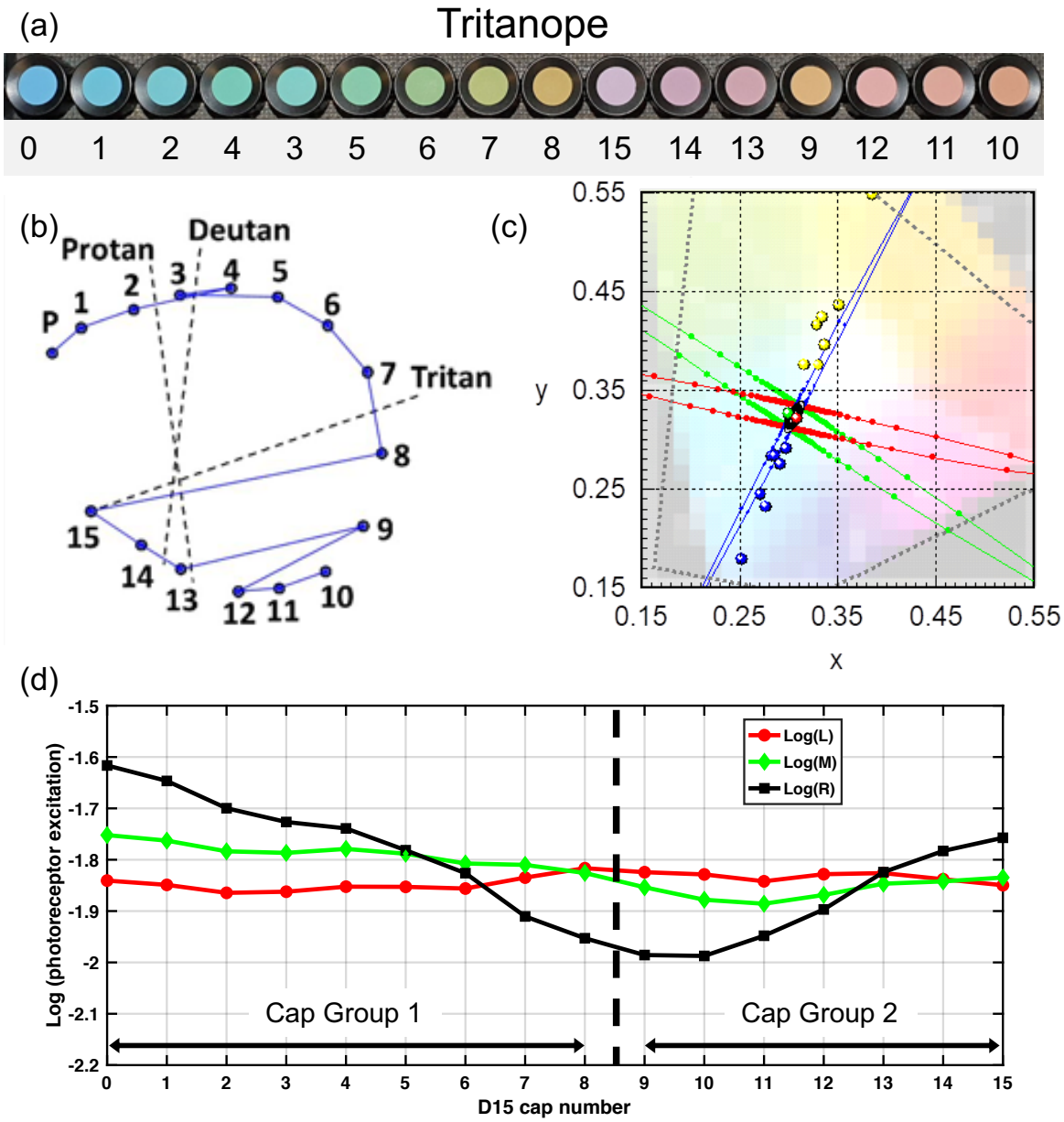

Figure 6. Measured data and theoretical photoreceptor excitations for a tritanope. Sections (a) and (b) show the recorded Farnsworth D-15 test results for an individual with tritanopia. The patient's CAD test results are shown in section (c). Section (d) shows the predicted photoreceptor excitations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

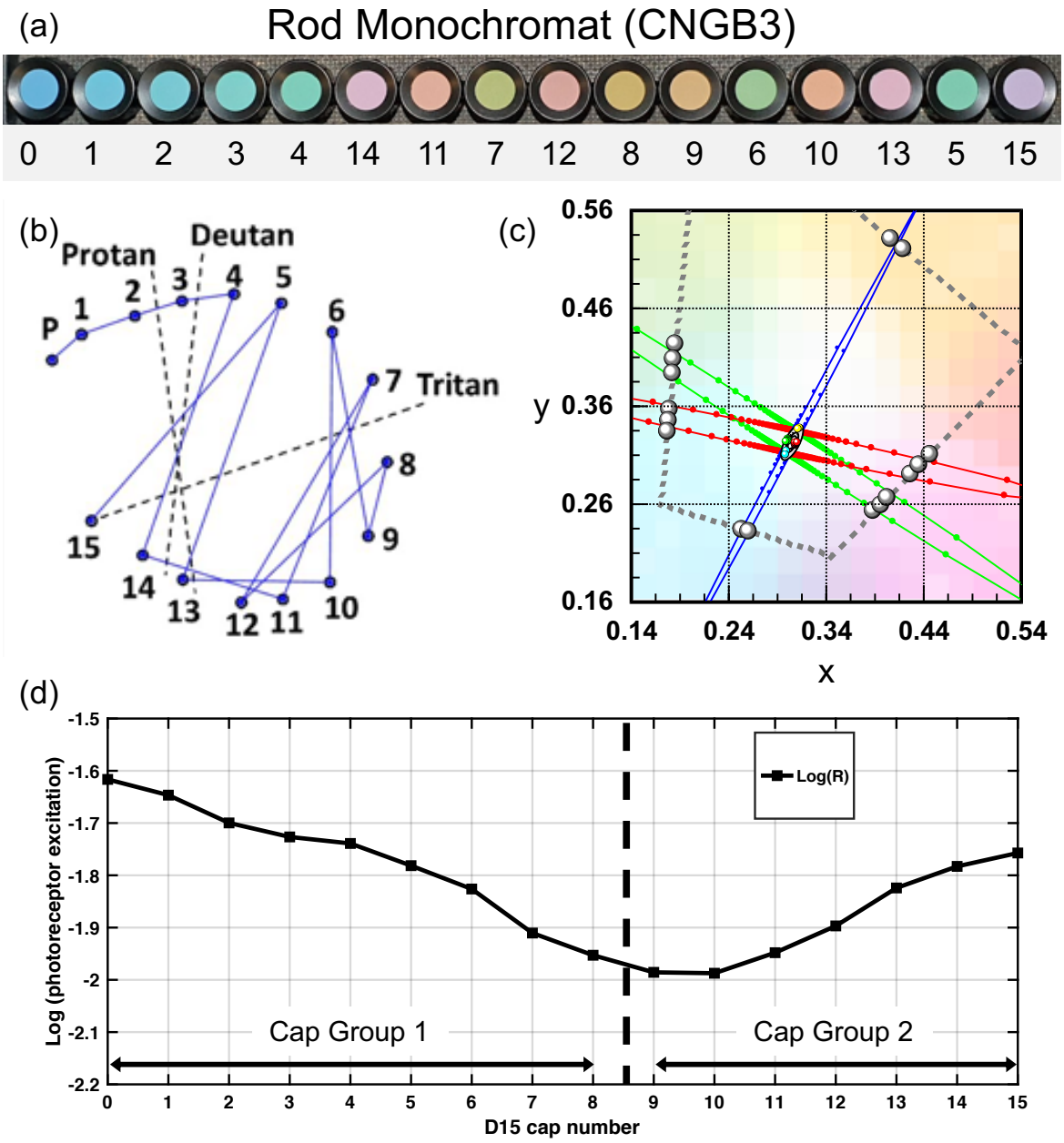

Figure 7. Measured data and theoretical photoreceptor excitations for a rod monochromat (CNGB3). Sections (a) and (b) show the recorded Farnsworth D-15 test results for an individual with rod monochromacy. The patient's CAD test results are shown in section (c). Section (d) shows the predicted photoreceptor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

Outcome of the Farnsworth D-15 test

Type of colour deficiency	Number of subjects	Percentage of subjects who pass using different pass criteria: No adjacent transpositions are accepted	Percentage of subjects who pass using different pass criteria: 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

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

457

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