Evaluation of a model to predict anomalous-observer performance with the 100-hue test

Jack Moreland,[1,*] Vien Cheung,[2] and Stephen Westland[2]

[1] *School of Life Sciences, Keele University, Staffordshire ST15 5AZ, UK*
[2] *School of Design, University of Leeds, Leeds LS2 9JT, UK*
**Corresponding author: j.d.moreland@keele.ac.uk*

Received October 3, 2013; revised December 2, 2013; accepted December 8, 2013;
posted December 12, 2013 (Doc. ID 198708); published January 24, 2014

Two subjects, protanomalous and deuteranomalous, performed the Farnsworth–Munsell 100-hue test with and without prescribed ColorView spectacle aids under simulated D65 lighting. Errors were greater with aids than without. Using spectral measurements of test reflectance, aid transmittance and lighting, chromaticities of the 100-hue caps were calculated with and without aids in the uniform chromaticity diagrams for protanomaly and protanomaly [Ophthalmol. Physiol. Opt. **30**, 685 (2010).]. Errors were modeled from chromatic spacing on a smoothed 100-hue locus together with a distractor term, derived from the distances of raw data from that locus. Good correspondence was found between the measured test and model profiles for the major maxima as well as other aspects of shape and position. © 2014 Optical Society of America

OCIS codes: (330.0330) Vision, color, and visual optics; (330.1720) Color vision; (330.4060) Vision modeling; (330.5370) Physiological optics.
http://dx.doi.org/10.1364/JOSAA.31.00A125

1. INTRODUCTION

The use of colored filters as aids for color defectives has been extensively reviewed and their ability to pass some color pigment-based tests has been attributed to changed luminance contrast. In particular, the ability of colored filters to break the camouflage of pseudoisochromatic plate tests without necessarily improving red–green color discrimination has been reported [1,2]. Alternatively, improved performance on the Farnsworth D15 test has been linked to the rotation of the test color locus in color space [3]. The Farnsworth–Munsell 100-hue test (100-hue), however, shows worsened performance [2,4]. A recent theoretical assessment of the change in red–green color discrimination for 43 commercial filter aids, using uniform chromaticity scale spaces for protanomaly (Pa) and deuteranomaly (Da), concluded that most (two thirds) reduced it and that none of the remainder provided a useful improvement [5]. The present paper uses those color spaces to develop models of the 100-hue test for Pa and Da. The model predictions of 100-hue performance of two anomalous trichromats, one Pa and one Da, with and without individually prescribed color vision aid lenses, are compared with their actual performance on the test.

2. METHOD

A. Subjects and Samples

Two subjects diagnosed by Rayleigh matches, using an Oculus HMC anomaloscope [6], as protanomalous (Pa) and deuteranomalous (Da) [7], were sent anonymously to an optometrist to be fitted with commercial color vision aids which are available in two models A (A1–A5) and B (B1–B3) [8]. They were chaperoned by one of the authors who observed the test procedure. The optometric examination began with a monitor screen version of the 100-hue test, to provide a differential diagnosis. That result determined the choice of model: A or B. A second monitor test, apparently based on pseudoisochromatic principles, involved the detection of the orientation of the short leg of a letter L (8 possible positions, 20 versions). The score in that test determined which lens was chosen from the selected series. Retest with that lens was done to confirm or modify the choice according to the test score.

There was no repeat of the 100-hue test with the chosen lens. Examination time was about 20 min. The lens aids prescribed for our two subjects were B1 for Pa and A5 for Da.

B. Test Procedure

We performed the actual 100-hue test under simulated D65 illumination at 741 lux, interlacing the unaided and aided conditions with intervals of 3 days or more over a period of more than 3 weeks. The 100-hue manual recommends retests “when a more precise diagnosis is needed” [9]. We used three tests for each condition (four for Pa unaided).

C. Measurement Devices

Spectral reflectance of the 100-hue caps was measured by reference to a white tile using a Konica Minolta CM2600d spectrophotometer. Spectral transmittances of A5 and B1 lenses were measured on a Shimadzu double-beam spectrophotometer [10] and the spectral power distribution of the simulated D65 illuminant was measured with a Konica Minolta CS1000 spectroradiometer (see Fig. 1).

D. Results

100-hue error scores were calculated according to Farnsworth’s method [11] and smoothed polar profiles of sessional averages plotted according to Kinnear [12] (see Fig. 2). Bipolar peaks for both unaided profiles fall in the respective ranges appropriate to Farnsworth’s portmanteau protan and

1084-7529/14/04A125-06$15.00/0

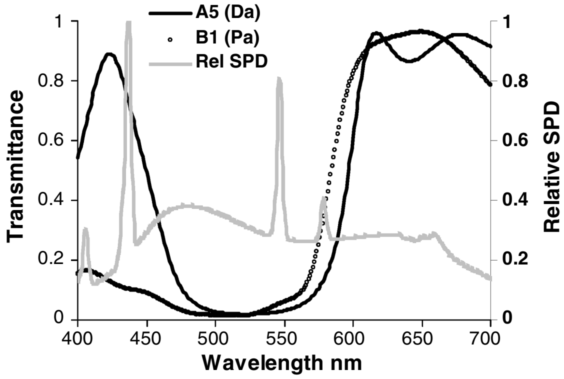

Fig. 1. Spectral transmittance profiles of two ColorView aids A5 and B1 and the relative spectral power distribution of the simulated D65 illuminant.

deutan classifications [13] and, to that extent, agree with the anomaloscopic diagnoses Pa and Da.

Wearing aids increased the errors of both subjects considerably and introduced a clockwise rotation of the profiles (see Fig. 2).

Using data in the range 400–700 nm at 1 nm intervals, tristimulus values with and without aids are computed by convolving average cone fundamentals for Pa and Da [14] with the spectral reflectance of the 100-hue caps illuminated by the simulated D65 illuminant. Chromaticities are computed in the approximately uniform Pa and Da chromaticity diagrams [15] (see Fig. 3).

3. MODEL

A. Smoothing the 100-Hue Locus

The rationale for defining a smooth locus was that this would provide a psychophysical equivalent to the hue and saturation cues used by Pa and Da in deciding on a smooth perceptual progression. Following the reassignment of cap numbers described in Section 4(i) below, radius lengths (measured from D65) are plotted as a function of "hue" angle (measured with respect to the horizontal through D65) and smoothed using a moving 15-point cubic spline. Smoothed chromaticities are then interpolated or extrapolated, as necessary, along their respective radii (see Fig. 6).

The model assumes that errors E are predicted by

$$E = \mathbf{a}(S - \mathbf{b}P) - \mathbf{c}, \tag{1}$$

where S is the average spacing for three consecutive smoothed chromaticities. P, a distractor term, is computed as follows. Take p_1, p_2, and p_3 as the perpendicular distances of three consecutive raw chromaticities from the smoothed 100-hue locus. Since the locus is not described by a single mathematical function, the actual distance computed is to

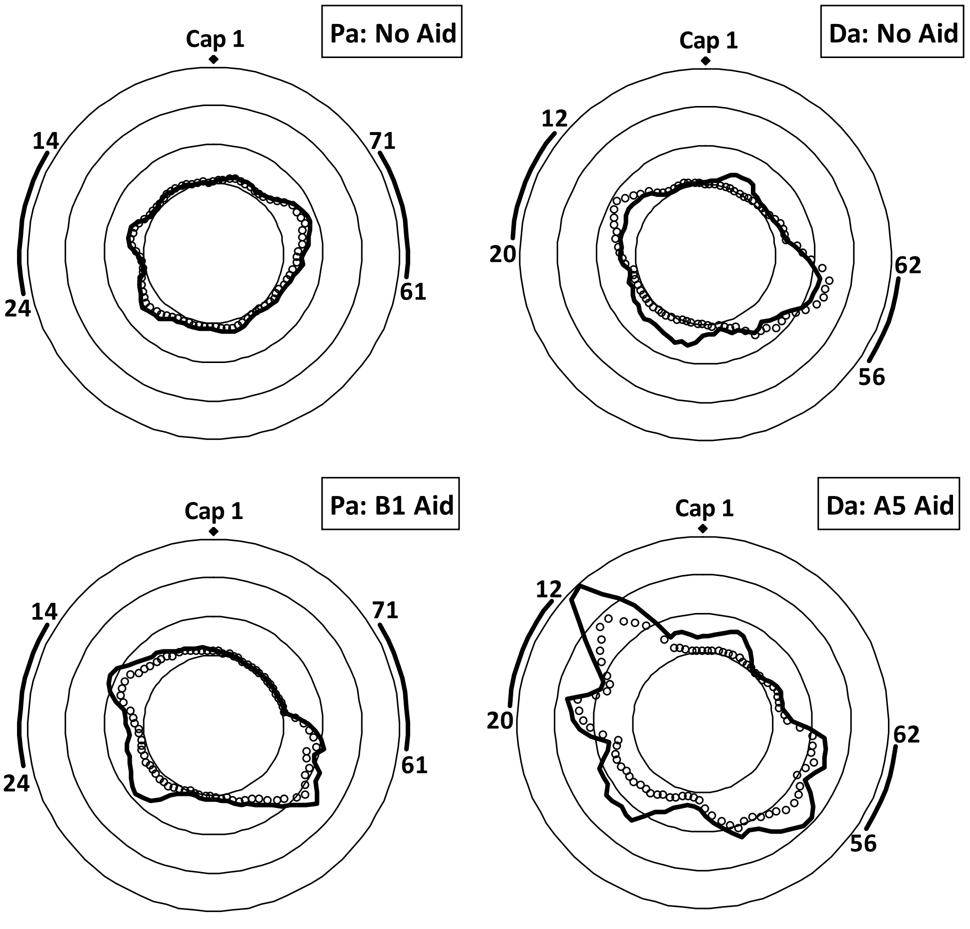

Fig. 2. Smoothed sessional average test error profiles. Circles: error scale—0, 5, 10, and 15. Arcs: cap number range of the protan and deutan (Farnsworth's portmanteau terms) peak error positions. Small empty circles: raw results. Black line: results with errors corrected for intersessional learning. Note: correction for learning increases all errors. Both aids increase errors and rotate the profiles clockwise.

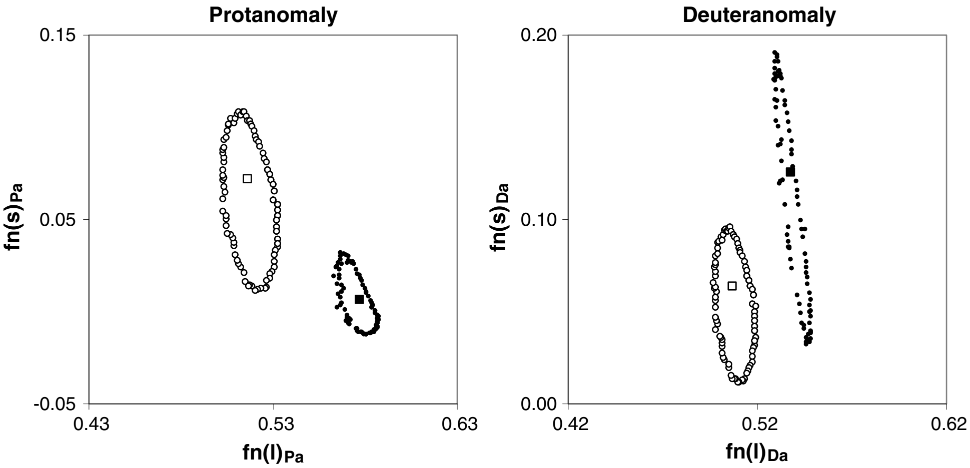

Fig. 3. Uniform chromaticity diagrams for protanomaly and for deuteranomaly. Axes, fn(l) and fn(s), are compressive transforms of the anomalous l and s cone excitations [5,15]. Circles: 100-hue caps. Squares: simulated D65 illuminant. Empty symbols denote no aid; filled symbols denote aid (ColorView B1 for Pa and A5 for Da). The aids shift the 100-hue locus bodily across the chromaticity chart: toward red for B1 and toward purple for A5. The 100-hue locus is compressed horizontally for both Pa and Da, reflecting their poor red–green discrimination; both the B1 and A5 aids compress that locus further.

the best straight line through the corresponding three smoothed points. Giving opposite signs to these distances according to whether the points lie inside or outside the smoothed locus, P is given by

$$P = \mathrm{ABS}(p_1 - p_2) + \mathrm{ABS}(p_2 - p_3) \qquad (2)$$

(this equation has the same form as that used by Farnsworth for computing cap error scores [11]). If, for example, the three distances are nearly equal but have the same sign, then P is small. But, if one of them has a different sign from the other two, P is much larger. This correlates with the subject's task in deciding whether three caps are correctly ordered. If all three chromaticities lie on the same side of the smoothed locus, then distraction would be minimal. Otherwise, distraction would be larger. Since, in many instances, the values of p are comparable or even greater than S, the contribution of the P to Eq. (1) may be quite large.

The scaling factors **a**, which is negative, **b** and the offset constant **c** are set by Excel Solver to maximize agreement with the test results.

B. Smoothing 100-Hue Error Profiles

First, the average of the three or four sessions is computed and then the resulting error profile is smoothed by a sliding five-point average.

C. Smoothing Model Error Profiles

Predicted errors are smoothed by a sliding nine-point average (comparable to 100-test error calculation with three to four sessions and five-point smoothing).

4. ANALYSIS AND DISCUSSION

The effect of learning on the 100-hue test has been documented [16]. Despite taking precautions to reduce that effect by interlacing and spacing tests over several days, total error scores (TESs) [17] fell over time. Aligning all data, except for session 1, revealed a similar trend for both subjects and both conditions (see Fig. 4). Taking account of this trend required intersessional increases in TESs of 21%. Average TESs are collected in Table 1. Intersessional variations in the shape of the polar error profile combine with the greater weight given to later sessions lead to shape changes between the raw and corrected polar profiles for Da but not for Pa (Fig. 2).

Wearing aids increased the TES of both subjects considerably (see Table 1).

As expected from their color appearance and transmittance profiles (Fig. 1), both filter aids shifted the 100-hue locus bodily across the chromaticity diagram: B1 toward the red and A5 toward purple. The locus is compressed horizontally (in the red–green direction) for both Pa and Da but compressed for Pa and expanded for Da vertically (in the

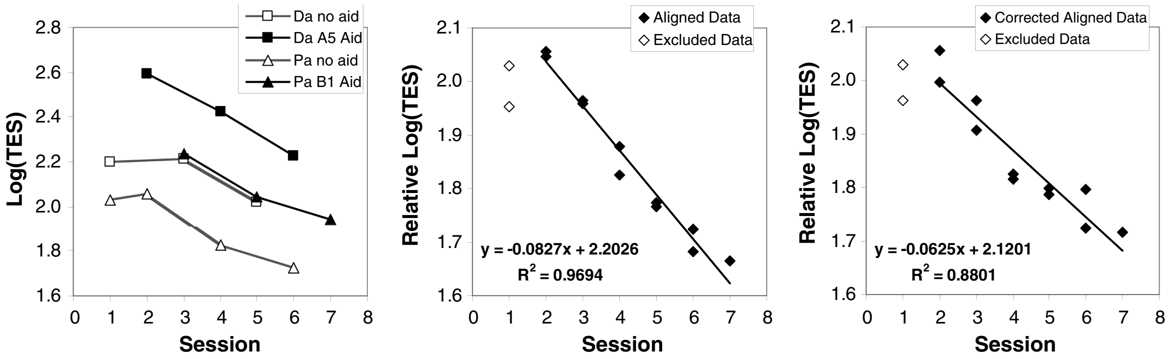

Fig. 4. Change of log (total error score) across sessions. Left panel: raw data. Center panel: data aligned with "Pa no aid": Session 1 is excluded from the regression. Right panel: as for center panel after reassigning cap numbers (see Section 4).

Table 1. Total Error Scores for the 100-hue Test

		Total Error Score		
		No Aid	Aided	Increase
Pa	Raw	85	124	1.5
	Corrected	109	199	1.8
Da	Raw	142	275	1.9
	Corrected	169	433	2.6

ColorView aids: B1 for the protanomal and A5 for the deuteranomal. "Corrected" involves cap reassignment and a learning correction for "Aided" but learning correction only for "No Aid".

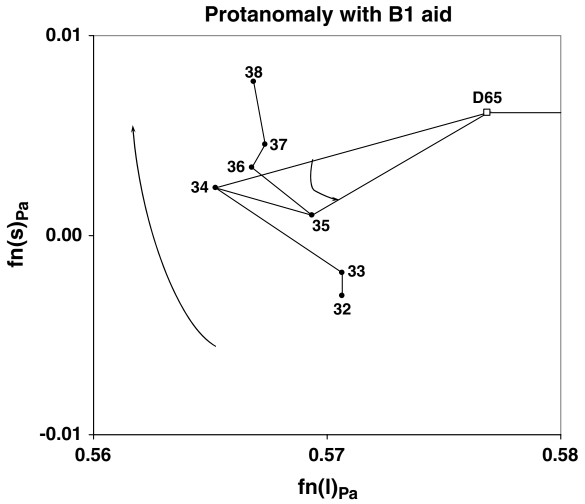
Protanomaly with B1 aid

Fig. 5. Disruption in chromatic order. Detail from the left panel of Fig. 3. The general trend for 100-hue caps is for their chromaticities to progress clockwise around D65. The change for caps 34 and 35 is anticlockwise; consequently, for the purpose of modeling, their numbers are interchanged. All such exceptions are similarly corrected so that "hue angle" measured with respect to the horizontal through D65 varies sequentially in one direction.

blue-yellow direction) (see Fig. 3). It is expected, from the oval shape of the 100-hue loci that Pa and Da subjects would use both hue and saturation cues to order caps during the test. The two aids also increased chromatic scatter and, unexpectedly, disrupted chromatic ordering (see Figs. 5 and 6). The filter-induced scatter far exceeds that deliberately incorporated by Farnsworth in the 100-hue test [18].

The effect of variations in ocular filters on changes in chromatic spacing of 100-hue caps for normal trichromats has been reported for the aging lens [19] and for macular pigment [20]. These analyses involved the use of a uniform chromaticity diagram to quantify chromatic crowding, rotation, and bodily shift of the 100-hue locus. In this paper, we extend the analysis to anomalous trichromats and introduce some refinements. Since a subject is required to arrange the 100-hue caps in a perceptually smooth progression, factors which affect that task should be included in a model to predict the 100-hue error profile. Consideration is given first to the disruption in chromatic order, next to chromatic scatter, and finally to the bodily shift of the 100-hue locus across the chromaticity diagram.

(i) Disrupted chromatic ordering. The general trend for 100-hue chromaticities is for cap numbers to progress clockwise around D65. Where reversal occurs (Fig. 5), cap numbers are reassigned to agree with the general trend. This affects both the calculation of 100-hue errors as well as the model.

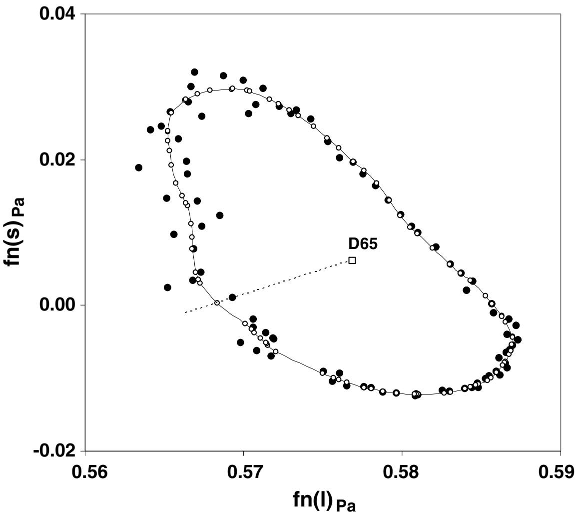

Fig. 6. Detail from the left panel of Fig. 3 with the aspect ratio of axes changed for clarity. Filled circles: 100-hue chromaticities for Pa with ColorView aid B1 illuminated by simulated D65. Empty circles: smoothed data extrapolated along radii (dotted line) through D65 and each raw chromaticity. The model uses the spacing of the smoothed data together with a distractor term, estimated from the distances of raw data from the smooth locus, in predicting 100-hue errors.

(ii) Chromatic scatter. This is dealt with in two parts. First, a smoothed locus is constructed through the raw 100-hue chromaticities (see Section 3 and Fig. 6). The model uses the spacing of data on that locus, together with a distractor term, estimated from the distances of raw data from the locus, in predicting 100-hue errors.

(iii) Bodily shift across the chromaticity diagrams. Since both the Pa and Da chromaticity diagrams were constructed to be approximately uniform, equal distances anywhere in each of them represent approximately equal color contrasts. Consequently, unlike the original highly nonuniform cone excitation diagrams from which the present ones were derived, no correction is required [5].

Allowing for both cap number reassignment and learning, model errors are computed from Eq. 1 (see Section 3). Following recalculation of the TES, the learning correction factor per session was reduced from about 21% to 16% (see Fig. 4, right panel). The 16% estimate applies to the data in Table 1. Model error profiles are shown in Fig. 7 (bottom panel) for both subjects and conditions.

The 100-hue test error profiles, corrected first for cap reassignment and then for learning (see right panel Fig. 4), are compared in Fig. 7 (top panel) with the model predictions (bottom panel).

The model correctly predicts general shape characteristics, such as bipolarity and orientation. In particular, the filter-imposed clockwise rotation of the 100-hue profile is replicated. Precise detail is not replicated but, bearing in mind that the model is based on cone fundamental averages for Pa and Da [14] and that large individual variations occur within each class, the correspondence is considered to be satisfactory.

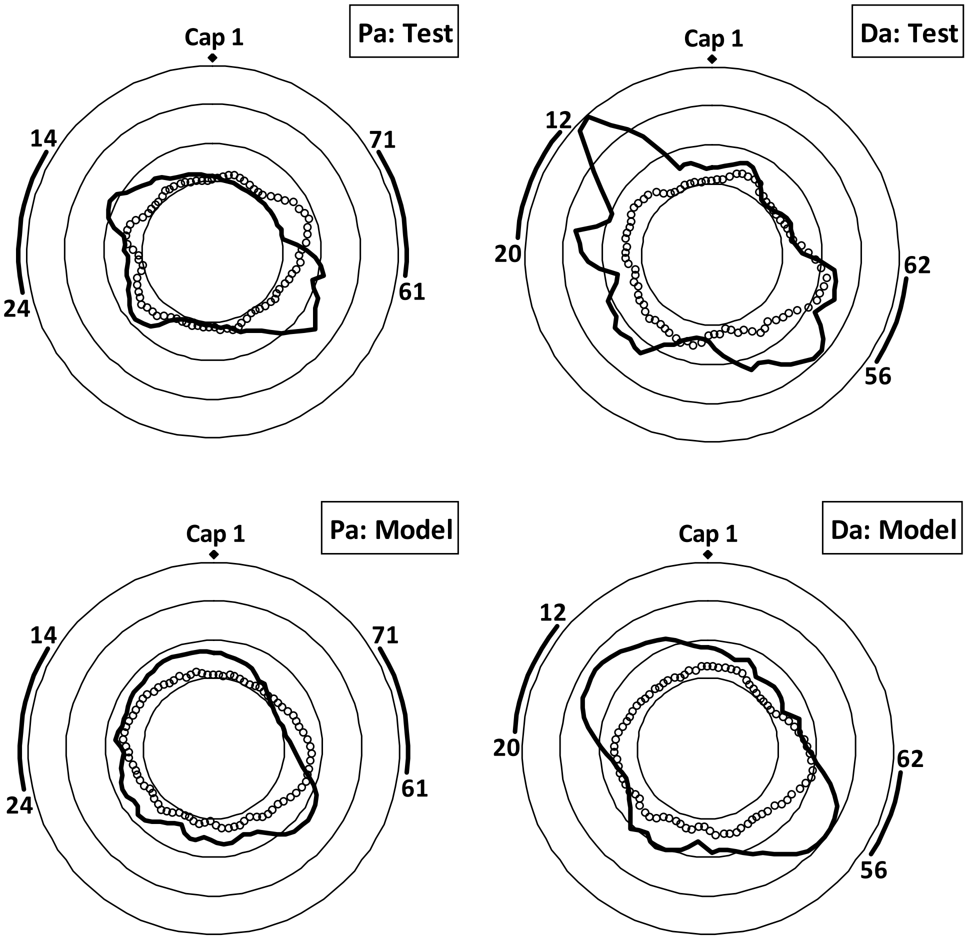

Fig. 7. Smoothed error profiles. As for Fig. 2. Small empty circles: no aid. Black line: ColorView aid worn (Pa—B1, Da—A5). Top: sessional average100-hue test results with caps reassigned and errors corrected for intersessional learning. Bottom: model based on spacing on a smoothed 100-hue locus combined with a distractor term derived from scatter around that locus.

These results confirm the robustness of the 100-hue test in assessing the ability or otherwise of colored lens aids to improve red–green discrimination of surface colors.

It is interesting to note, in this context, that the optometric examination for prescribing the aids employed a version of the 100-hue test. However, that was used for differential diagnosis only and only once. The examination resorts to a potentially less robust pseudoisochromatic test in deciding on the effectiveness of a trial aid. Whether the decision to examine in that way reflects the manufacturer's understanding of the colorimetric issues may be illustrated with an extract from their website "*ColorView® Lenses are designed to help distinguish colors easier. Regular eyeglasses help focus images, ColorView® glasses help focus light!*" [8].

The present paper attempts to approach the subject with more rigor.

ACKNOWLEDGMENT

Supported by the Clothworkers' Innovation Fund C1021.

REFERENCES AND NOTES

1. I. Schmidt, "Visual aids for correction of red-green colour deficiencies," Can. J. Optom. **38**, 38–47 (1976).
2. L. T. Sharpe and H. Jägle, "I used to be color blind," Color Res. Appl. **26**, S269–S272 (2001).
3. S. P. Taylor, "The X-Chrom lens: does it have any effect on colour perception of colour-deficient observers," Doc. Ophthalmol. Proc. Ser. **46**, 467–471 (1987).
4. M. Siegel, "The X-Chrom lens. On seeing red," Surv. Ophthalmol. **25**, 312–324 (1981).
5. J. D. Moreland, S. Westland, V. Cheung, and S. J. Dain, "Quantitative assessment of commercial filter 'aids' for red-green colour defectives," Ophthalmol. Physiol. Opt. **30**, 685–692 (2010).
6. H. Krastel, H. Gehrung, K. Dax, and K. Rohrschneider, "Clinical application of the Heidelberg anomaloscope," Doc. Ophthalmol. Proc. Ser. **54**, 135–149 (1991). This anomaloscope employs a 2° bipartite field with narrow bandwidth stimuli. One half is a yellow (589 nm) and the other a mixture of red and green (664 nm and 548 nm). Rayleigh matches are metameric foveal color matches made between the two half-fields.
7. Color matches made by anomalous trichromats are shifted from those of normal trichromats; matches with excess red in the mixture diagnose protanomaly while those with excess green diagnose deuteranomaly.
8. http://www.color-view.com/products.php#model.
9. D. Farnsworth, *The Farnsworth-Munsell 100-Hue Test: For the Examination of Color Discrimination* (Munsell Color Company, 1957).
10. Courtesy of Prof. Ron Douglas, City University, London, U.K.
11. The 100 hue manual states, "The score for a cap is the sum of the (absolute) differences between the number of that cap and the numbers of the caps adjacent to it."
12. P. Kinnear, "Proposals for scoring and assessing the 100-hue test," Vis. Res. **10**, 423–433 (1970).
13. Farnsworth coined portmanteau terms which cover anomalous trichromacy and dichromacy: protan for protanomaly and protanopia and deutan for deuteranomaly and deuteranopia.

14. P. DeMarco, J. Pokorny, and V. C. Smith, “Full-spectrum cone sensitivity functions for X-chromosome-linked anomalous trichromats,” J. Opt. Soc. Am. A **9**, 1465–1476 (1992).
15. Reference [5]. The compressive equation converting the long wavelength cone excitations l to a uniform scale is $\text{fn}(l) = a \log([l_p]^b + c$, where l_p is a projective transform of l and a, b, and c are constants which optimize uniformity of the $\text{fn}(l)$ scale. The equation for $\text{fn}(s)$ has the same form but with different constants. The $\text{fn}(s)$ scale of Ref. [5] is reduced here by a factor of 5 to harmonize with the $\text{fn}(l)$ scale.
16. G. Verriest, J. V. Laethem, and A. Uvijls, “A new assessment of the normal ranges of the 100 hue total scores,” Doc. Ophthalmol. Proc. Ser. **33**, 199–208 (1982).
17. The 100 hue cap score for a correct arrangement is 2, which is subtracted in summing the total error score.
18. Farnsworth incorporated “slight differences” to require “some aptitude in normals” and to detect “color defectives by forcing them to resort to criteria other than hue difference.”
19. K. H. Ruddock, “Light transmission through the ocular media and macular pigment and its significance for psychophysical investigation,” in *Visual Psychophysics*, *Handbook of Sensory Physiology*, D. Jameson and L. M. Hurvich, eds. (Springer, 1972), Vol. **7/4**, pp. 455–469.
20. J. D. Moreland and S. L. Dain, “Macular pigment contributes to variance in 100 hue tests,” Doc. Ophthalmol. Proc. Ser. **57**, 517–522 (1995).