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A model for assessing the efficacy of colour vision aids

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Abstract: Optical filter aids are marketed which claim to improve colour discrimination in red-green colour vision defectives. An earlier model has been revised and used to assess 9 currently available aids. Spectral reflectances (400-700 nm) for 80 colours equally spaced in hue angle at four equally spaced saturations were synthesised from chromatically adjacent Munsell colours. Aid induced chromaticity changes for Protanomals and Deuteranomals were calculated. Five aids enhanced red-green discrimination significantly for Protanomals and six for Deuteranomals and one aid reduced it significantly for both defectives. Five aids enhanced blue-yellow discrimination in Protanomals and Deuteranomals for whom it is not needed.

1. Introduction

Moreland et al. [1] have published uniform chromaticity scales (UCS) for Normals (N), Protanomals (Pa) and Deuteranomals (Da) and used them as a metric to assess the efficacy of 43 commercial optical filter aids that were available around 2010. The model based the assessment of such aids on the UCS colour changes which they produced to the Munsell colour chips of the Farnsworth D15 test. The model was used also to assess filter efficacy on the Farnsworth-Munsell 100 hue test [2]. That model is now revised: partly to avoid confusing it with colour vision testing but, perhaps more significantly, changing to a more representative colour set of 80 defined in the Normal UCS, disposed in 4 equi-spaced saturation levels each containing 20 equi-spaced samples. As before, spectral transmittances of the aids are measured and tristimulus values with and without aids are computed using the DeMarco et al. [3] cone fundamentals and the spectral power distributions of the samples illuminated by CIE Illuminant D65 (D65). This illuminant is recommended by the CIE as representing average daylight [4]. Chromaticities fn(l),fn(s) are computed from projective-logarithmic transforms [1] of L/(L + M), S/(L + M) where L, M and S are the long, medium and short wavelength cone sensitivity functions of DeMarco et al. [3] and L and M are specific to N, Pa or Da. The transforms are used to generate approximate UCS diagrams for N, Pa and Da unaided and for Pa and Da aided. Nine more recent aids are included in this study. These have absorbing notches with varying depth, width and multiplicity, Fig. 1.

2. Method

Transmittance measurements were carried out in the Optics & Radiometry Laboratory, School of Optometry and Vision Science, UNSW. The spectral transmittances, 400-700 nm in 1 nm steps, were measured using Varian Cary model 5000 UV-Vis-NIR spectrophotometers in dual beam mode (Agilent, Santa Clara, USA). The spectral half bandwidth was 2 nm and wavelength accuracy was ± 0.1 nm verified by spectral lines in the mercury, neon and deuterium discharge spectra. The linearity was measured using a set of grey glass filters for which calibration data has been obtained from the National Research Council of Canada. Two identical spectrophotometers

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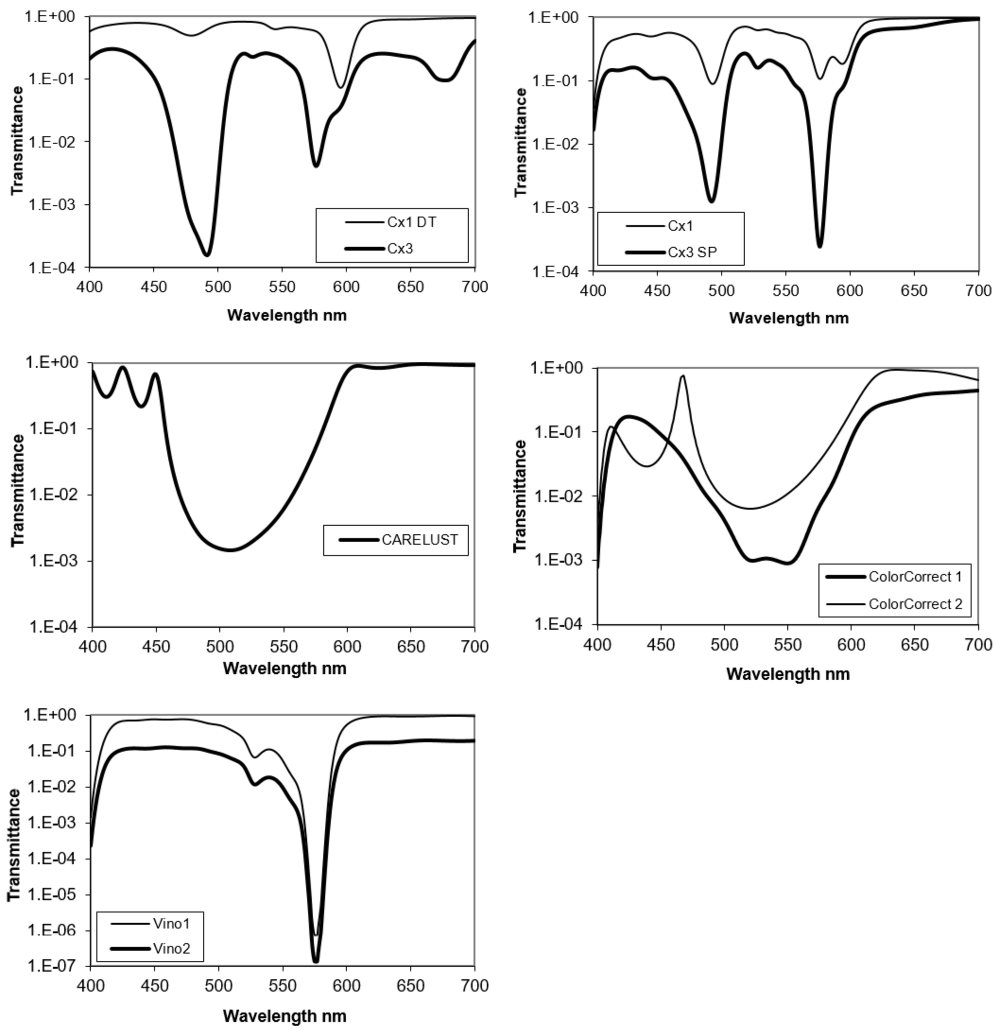

Fig. 1. Spectral transmittance (logarithmic scale) for 9 lenses (Top pair of graphs: EnChroma).

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were used depending on availability. Both lenses of a pair were measured on the same instrument. The measurements were made at normal incidence at the boxed centre [5] of an edged lens or the geometric centre of an uncut lens. Averages for two lenses were used in calculations. The Optics & Radiometry Laboratory, UNSW, is accredited to ISO/IEC 170257 [6] as a calibration laboratory for direct spectral transmittance. Seven lenses were acquired online directly from their manufacturers: EnChroma (2), Carelust (1), ColorCorrect (2) and Vino (2). The EnChroma Cx1 DT and Cx3 were acquired on loan basis.

Exact spectra underlying the 80 targets (Fig. 2) are computed by combining the spectra of three near-neighbour Munsell colours (selected from 1269 Munsell matte papers [7]) under D65 which form a small triangle in the UCS u_1,v_1 diagram [1] enclosing the target so that the chromaticity of the combination matches that of the target. The UCS diagram employs Vos' [8] revision of the CIE colour matching functions.

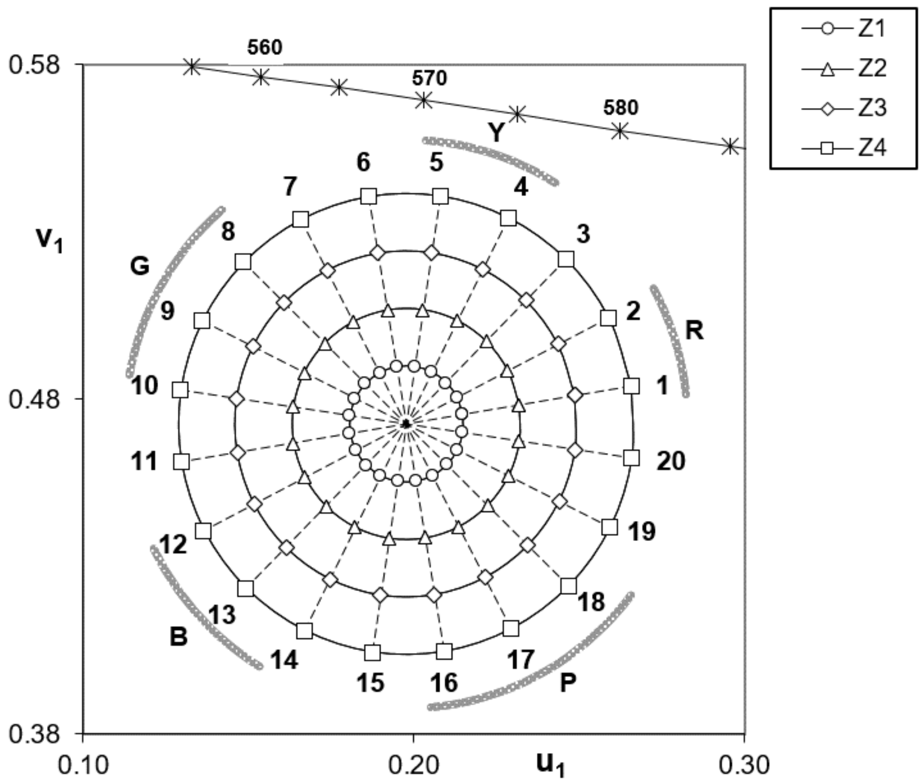

Fig. 2. Chromaticities in the Normal UCS [1] diagram of 80 target colours arranged in circular zones Z1, Z2, Z3 and Z4 centred on D65 with radii in the ratio 1:2:3:4. The diameter 10-20 is set parallel to the long wave end of the spectrum locus. Grey arcs indicate the approximate angular extent of Munsell principal hues R Y G B & P.

Using spectral transmittance 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 N, Pa and Da [3] with the spectral power distributions of the 80 samples illuminated by D65. Chromaticities are computed for N and for the Pa and Da analogues of the MacLeod and Boynton [9] diagram in terms of the relative excitation of their long (L), medium (M) and short (S) wavelength sensitive cones. Chromaticities fn(l),fn(s) are projective-logarithmic transforms [1] of L/(L + M), S/(L + M).

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3. Results and discussion

Figure 3 (left) shows four zones of 20 virtual sample colours each for unaided N, Pa and Da in the approximate UCS [1] transforms of their cone excitation diagrams. Sample numbering runs clockwise. Munsell Primary hue notation (R, Y, G & B) refers to Normal vision under D65. All scale ranges are 0.145 and colours are centred in each graph for visual comparison. Even numbered radii are omitted for clarity.

Since only changes parallel to the UCS ordinate and abscissa were considered in our earlier study [1] there was no need to harmonise the two scales. However, this study includes saturation effects and requires the introduction of a harmonising factor. The fn(s) scale is harmonised here with fn(l) for N by dividing its values by 5.05. The same is applied to Pa and Da.

Compared to N, both Pa and Da are compressed parallel to the abscissa fn(1) reflecting their reduced Red-Green discrimination. They would require aid-induced expansions of some 3-fold and 4-fold respectively to approach N discrimination in that direction. We have proposed a 2-fold expansion as a useful target for optical filter aids [1]. No change is needed parallel to the ordinate fn(s) since Blue-Yellow discrimination is not significantly different from N. Note that the straightness of hue lines, set by design for N, are reasonably conserved for Pa and Da.

Figure 3 (right) shows that the EnChroma Cx3 SP aid produces for both Pa and Da overall expansions in the 'Red-Green' discrimination direction (parallel to the abscissa) but compressions in the 'Blue-Yellow' direction (parallel to the ordinate). Note also that some hue lines, notably 9-11 and 19 become distorted.

Standard deviations of fn(l) and fn(s) values are computed for the 4 saturation sets of samples and enhancement factors E_l and E_s are derived as the ratio of aided to unaided standard deviations. Luminous transmittances of aids are computed using the M and L fundamentals respectively as the relative luminous efficiency functions for Pa and Da. Numerical results are shown in Table 1.

The following remarks refer to average E values for all saturation zones in Table 1. The table reveals no systematic trends across the four zones.

Enhanced Red-Green discrimination ($E_l > 1$) is found for all 4 EnChroma lenses for Da but only for 3 (Cx1, Cx3 and Cx3 SP) for Pa. Uniquely, Cx3 SP has an E_l close to our recommended [1] utility value 2 ($E_l \approx 1.8$ for Pa and 1.7 for Da) but at the expense of significantly reduced Blue-Yellow discrimination ($E_s \approx 0.7$).

Da performance is better for Cx1 DT and Cx3 than for Cx1 and Cx3 SP and the converse applies for Pa. However, the differences found are quite small.

The Cx3 SP lens shifts D65 and all zones towards the spectrum locus (Figs. 3 and 4) and displays the expected crowding effect for Zone 4 (Fig. 5) and even for Zone 3 (Fig. 6). Since spectral stimuli are strictly monochromatic filters have no effect on its chromaticity. The spectrum locus is effectively an immoveable barrier. But for both Pa and Da, the distance from unaided D65 is reduced more for sample 5 than for the diametrically opposed sample 15 when aided than when not (Fig. 5). Comparing sample saturation ratios (5/15) for all four zones (Fig. 6) shows that the crowding effect is noticeable also in Z3 but undetectable in Z1 and Z2 which are closer to unaided D65.

Carelust lenses reduce Red-Green discrimination ($E_l < 1$) significantly. Carelust, ColorCorrect and Vino lenses all enhance Blue-Yellow discrimination ($E_s > 1$) where it is not needed by either Pa or Da.

Vino lenses 1 and 2 both enhance E_l by a modest amount, slightly more for Vino 2 but at the expense of a significant reduction of luminous transmittance.

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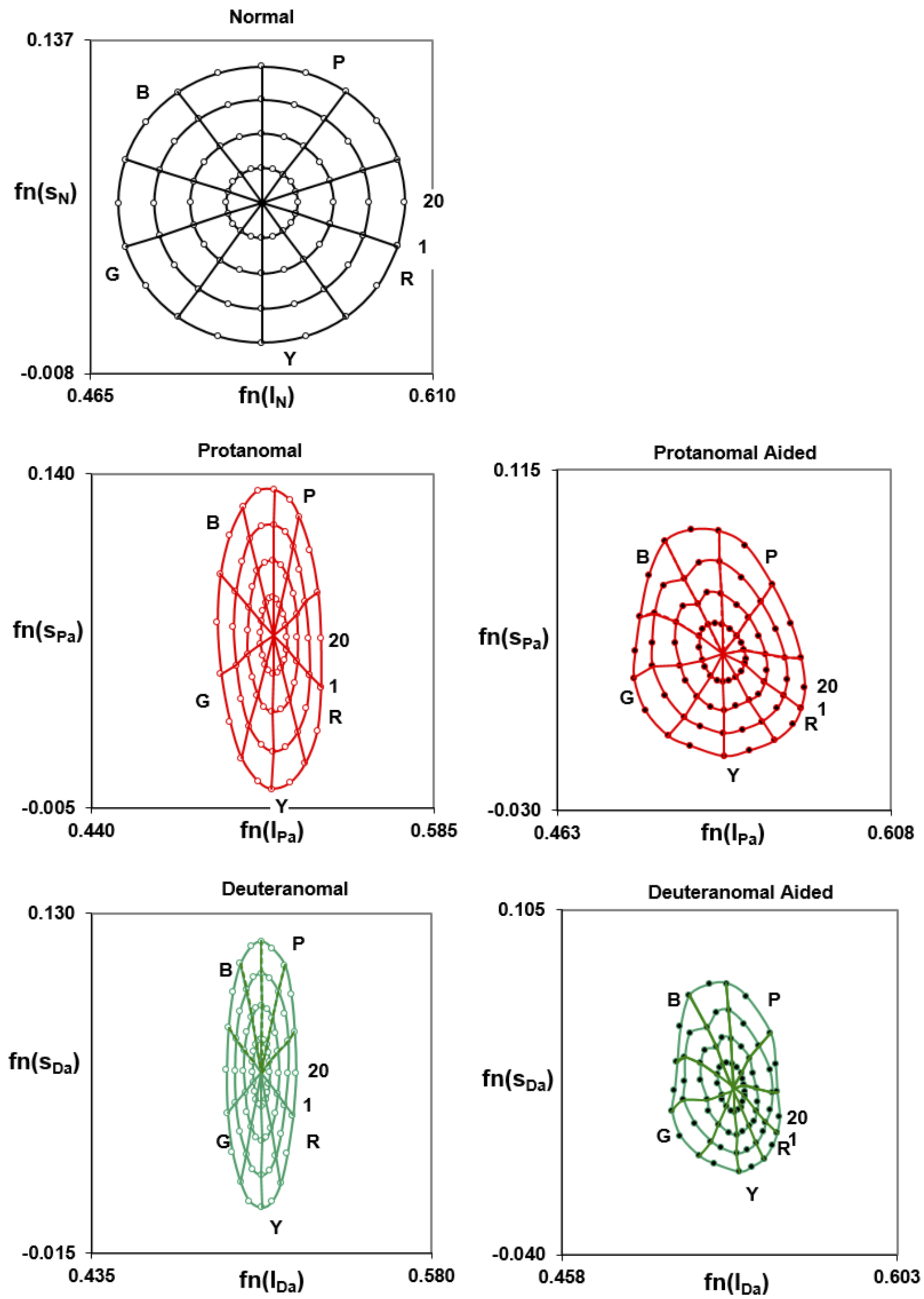

Fig. 3. Four zones of 20 virtual sample colours each for unaided N, Pa and Da (left) and for Pa and Da aided by EnChroma Cx3 SP (right). Note that all scale lengths have been set equal at 0.145 to facilitate comparison.

Table 1. Values of E_l and E_s for Pa and Da. Luminous transmittance applies to D65

Zone	Aid		EnChroma				Carelust	ColorCorrect		Vino	
			Cx1	Cx1 DT	Cx3	Cx3 SP	Colospecs	1	2	1	2
All	**Pa**	E_l	1.24	1.01	1.25	1.78	0.52	0.92	1.08	1.39	1.44
		E_s	0.98	1.05	1.02	0.72	1.40	1.61	1.24	1.34	1.34
	Da	E_l	1.36	1.18	1.36	1.66	0.63	0.97	1.09	1.27	1.29
		E_s	0.97	1.05	1.01	0.68	1.48	1.68	1.26	1.36	1.36
1	**Pa**	E_l	1.23	1.00	1.26	1.78	0.49	0.89	0.99	1.31	1.37
		E_s	1.00	1.06	1.08	0.75	1.43	1.62	1.19	1.31	1.33
	Da	E_l	1.38	1.18	1.42	1.62	0.59	0.89	1.00	1.23	1.25
		E_s	0.98	1.06	1.07	0.71	1.51	1.70	1.19	1.34	1.35
2	**Pa**	E_l	1.25	1.00	1.27	1.83	0.54	0.97	1.09	1.38	1.44
		E_s	0.99	1.06	1.06	0.75	1.43	1.64	1.23	1.33	1.34
	Da	E_l	1.38	1.19	1.39	1.65	0.64	0.93	1.07	1.26	1.28
		E_s	0.98	1.05	1.04	0.70	1.51	1.72	1.24	1.35	1.36
3	**Pa**	E_l	1.26	1.02	1.27	1.84	0.55	0.97	1.13	1.41	1.47
		E_s	0.98	1.05	1.02	0.72	1.40	1.61	1.26	1.32	1.33
	Da	E_l	1.38	1.19	1.37	1.70	0.65	0.96	1.12	1.27	1.29
		E_s	0.96	1.04	1.00	0.68	1.49	1.69	1.28	1.34	1.34
4	**Pa**	E_l	1.23	1.01	1.23	1.74	0.50	0.88	1.04	1.38	1.44
		E_s	0.98	1.05	1.01	0.72	1.39	1.60	1.24	1.35	1.34
	Da	E_l	1.34	1.18	1.34	1.64	0.61	0.99	1.08	1.27	1.29
		E_s	0.96	1.04	1.00	0.67	1.47	1.66	1.26	1.36	1.35
Luminous Transmittance		**Pa**	0.46	0.65	0.14	0.13	0.09	0.02	0.06	0.22	0.04
		Da	0.49	0.62	0.14	0.19	0.24	0.06	0.16	0.28	0.05

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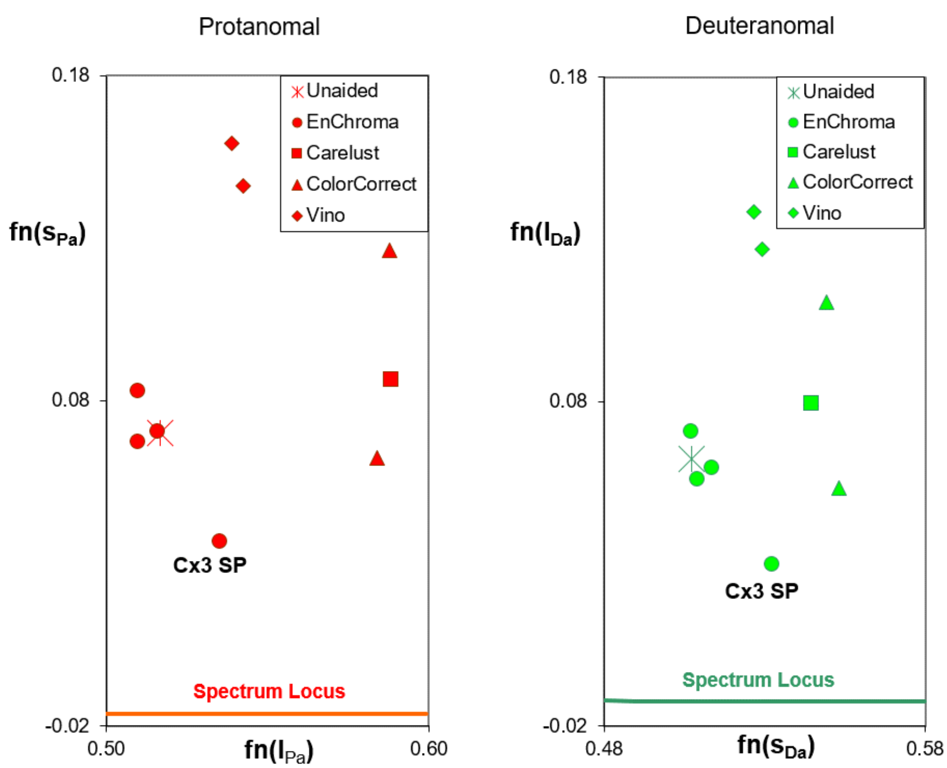

Fig. 4. Chromaticities of D65 alone and seen through 9 filter aids. Three EnChroma filters are nearly neutral but Cx3 SP is unique in the extent to which it shifts D65 down towards the spectrum locus.

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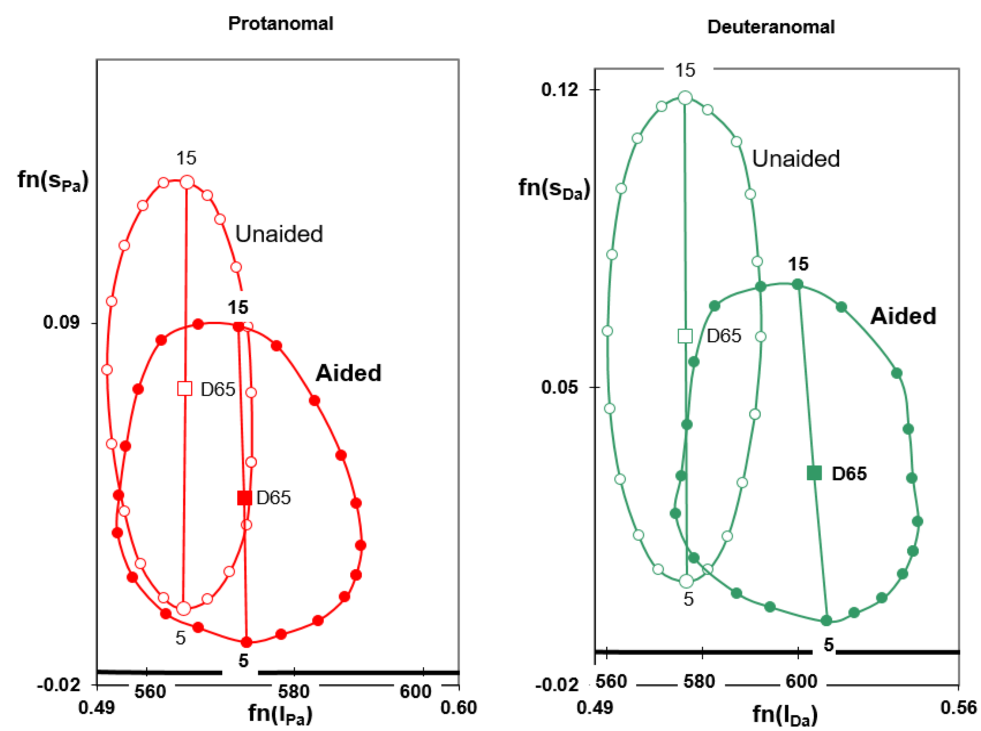

Fig. 5. Effect of EnChroma lens Cx3 SP on zone 4 samples for Pa and Da.

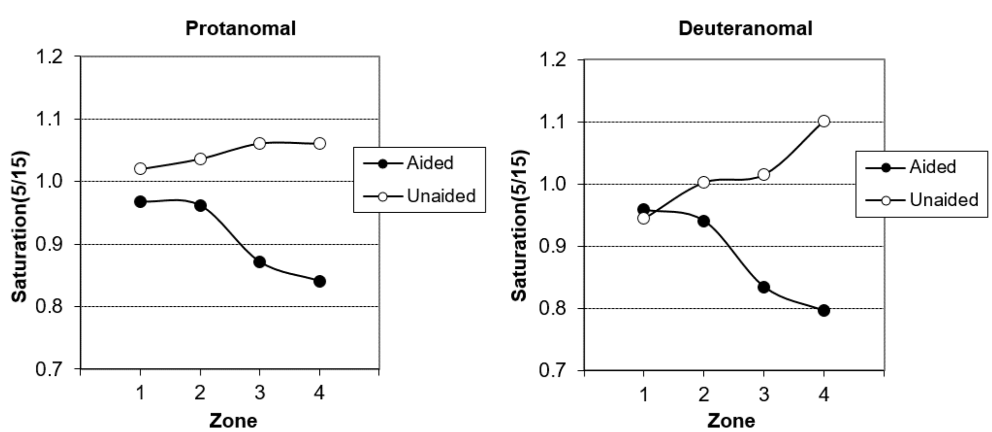

Fig. 6. Effect of EnChroma Cx3 SP on the saturation ratios for samples 5 and 15 for all four zones.

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4. Conclusions

Of the 9 lenses assessed only Cx3 SP has an E_l close to our recommended [1] utility value 2 (about 1.8 for Pa and 1.7 for Da) but at the expense of reduced Blue-Yellow discrimination ($E_s \approx 0.7$).

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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