The Display Gamut Available to Simulate Colors Perceived by Anomalous Trichromats

João M.M. Linhares[1(✉)], Jorge L.A. Santos[2], Vasco M.N. de Almeida[2], Catarina A.R. João[1], Sérgio M.C. Nascimento[1]

[1] Center of Physics, Campus Gualtar, University of Minho, 4710-057 Braga, Portugal
{jlinhares,smcn}@fisica.uminho.pt, car.joao89@gmail.com
[2] Department of Physics, University of Beira Interior, 6201-001 Covilhã, Portugal
j.l.a.santos@gmail.com, vasco@ubi.pt

Abstract. The aim of this work was to investigate the effect on a display gamut of varying the optical density and the position of the maximum sensitivity of the cones spectra of anomalous trichromatic observers. The anomalous cone spectral sensitivities were estimated for a set of varying optical density and maximum sensitivity spectra conditions and used to compute the display color gamut. The computed display gamut simulated for normal observers the chromatic diversity perceived by anomalous observers. It was found that even small variations on the optical density and on the position of the maximum sensitivity spectra have an impact on the simulations of the display gamut for anomalous observers. It was also found that simulations for deuteroanomalous observers are the ones with greater impact if the estimation of the corresponding color display gamut is not carefully adjusted for the observer.

Keywords: Anomalous color vision · Color gamut · Color deficient

1 Introduction

The chromatic diversity experienced by normal color vision observers encloses millions of individually discernible colors [1]. These cones are sensitive to the long, middle and small regions of the visible spectrum and are denominated L, M and S-cones, respectively [2]. Anomalous trichromats observers still retain the functional use of the three color sensors, but their spectral sensitivity by the means of a pigment that is photosensitive to visible light is different from the normal color vision observer on the M and L cones [3], [4] and are named deuteroanomalous and protoanomalous, respectively. The differences in the spectral sensitivity of anomalous observers will impair their color vision [5], [6] and might limit their ability to perform some tasks [7]. This limitation is found to be the confusion of some colors that are identified as different by normal color vision observers with a direct impact on color vision perception [8], [9].

The simulation of anomalous color vision as perceived by normal observers is then of valuable use when trying to ascertain anomalous colored vision perception, as by doing so improvements to their color vision might be attempted [10], [11].

A. Trémeau et al. (Eds.): CCIW 2015, LNCS 9016, pp. 104–110, 2015.
DOI: 10.1007/978-3-319-15979-9_10

This simulation is very dependent on the spectral sensitivity of the anomalous cones, the concentration of photopigment available at each individual class of cones (or their optical density) and ocular media transparency [3], [8], [12]. Small variations on each of these quantities will have an impact on anomalous color vision, which might compromise proper color vision assessment by the means of computer color vision tests [13].

The purpose of this work is to study how variations on the optical density and spectral sensitivity of anomalous cones impact the display color gamut simulated for normal observers as a perception of anomalous observers color vison. Simulations of anomalous color vision were computed by fixating the anomalous spectral shift and by independently varying the M or L cones optical density or by fixating the optical density of the M and L cones and varying their spectral position. In each case the simulation of the display color gamut was estimated and its area in CIE 1976 UCS [14] computed as a measurement of the chromatic impact in anomalous color vision. The results obtained here seem to show that each condition variation affects at least 20% on the simulated gamut, amount that can be around 70% in some extreme conditions.

2 Methods

2.1 General Estimation of the Anomalous Cone Spectral Sensitivity Curve

The method used to estimate the anomalous cone sensitivities to simulate for normal observers the colors perceived by anomalous observers was the one described elsewhere [3]: a normal cone spectral sensitivity curve estimated at the cornea [2] was used as template. Average normal observer lens and macular pigment absorption spectra [3] were used to estimate the spectral sensitivity at the retina [15]. The cone photopigment optical density was then corrected for self-screening assuming the original maximum optical (OD_{max}) and converted into wavenumber to ensure that the wavelength shift was shape independent [16]. The shift was then produced as desired. To reconstruct the anomalous spectral sensitivity curve at the cornea the reversed process was used: the shifted spectrum was converted into wavelength, corrected for self screening and for lens and macular pigment absorption. All computations were done in quantal. Whenever conversion from energy to quantal was needed energy data was divided by its corresponding wavelength.

2.2 Estimating Protoanomalous Spectral Sensitivity Curve

Three assumptions were made to estimate the protoanomalous (L') spectral sensitivity curve:

1. M cone was used as template and MOD_{max} was used to compensate for self screening;
2. After shifting the M cone spectral sensitivity spectra towards longer wavelengths the self screening was compensated using the normal LOD_{max} to obtain anomalous L cone sensitivity spectra or L';

3. The amplitude of the L' cone spectral sensitivity was assumed to be equal to the normal L cone.

Using these three assumptions, the L' anomalous cone spectral sensitivity was estimated by:

(a) Fixating the spectral shift in 10 nm and the MOD_{max} to 0.3 and vary the LOD_{max} from 0.3 to 0.5 in 0.01 steps;
(b) Fixating the spectral shift in 10 nm and the LOD_{max} to 0.4 and vary the MOD_{max} from 0.2 to 0.4 in 0.01 steps;
(c) Fixating the LOD_{max} to 0.4 and the MOD_{max} to 0.3 and vary the spectral shift towards longer wavelength from 5 to 15 nm in 0.5 nm steps;

2.3 Estimating Deuteroanomalous Spectral Sensitivity Curve

Three assumptions were made to estimate the deuteroanomalous (M') spectral sensitivity curve:

4. L cone was used as template and LOD_{max} was used to compensate for self screening;
5. After shifting the L cone spectral sensitivity spectra towards shorter wavelengths the self screening was compensated using the normal MOD_{max} to obtain anomalous M cone sensitivity spectra or M';
6. The amplitude of the M' cone spectral sensitivity was assumed to be equal to the normal M cone.

Using these three assumptions, the M' anomalous cone spectral sensitivity was estimated by:

(d) Fixating the spectral shift in 6 nm and the MOD_{max} to 0.3 and vary the LOD_{max} from 0.3 to 0.5 in 0.01 steps;
(e) Fixating the spectral shift in 6 nm and the LOD_{max} to 0.4 and vary the MOD_{max} from 0.2 to 0.4 in 0.01 steps;
(f) Fixating the LOD_{max} to 0.4 and the MOD_{max} to 0.3 and vary the spectral shift towards shorter wavelength from 2 to 10 nm in 0.5 nm steps;

2.4 Estimating the Display Color Gamut

The three phosphors of a CRT monitor (Sony Trinitron GDM-F520, Sony Corp., Japan) were measured using a calibrated telespectroradiometer (PR-650 SpectraScan Colorimeter; Photo Research, Chatsworth, CA). The stimulus was presented in the display by using a video display card (ViSaGe Visual Stimulus Generator; Cambridge Research Systems, Rochester, Kent, UK) to power each phosphor individually at its maximum intensity. The measured spectral radiance was then converted into CIE 1976 UCS chromaticity coordinates [14] assuming each cone sensitivity spectra estimated in (a) to (f). The CIE 1931 standard observer was assumed on all estimations [14].

The CIE 1976 UCS chromaticity coordinates were then used to estimate the triangular color gamut. The area occupied by it was estimated by using a convex hull algorithm available in MatLab (MathWorks, Inc., Natick, MA, United States of America) which is based on the Qhull algorithm [17]. The estimated area was then normalized to its maximum to estimate the variations on the color gamut across the (a) to (f) conditions.

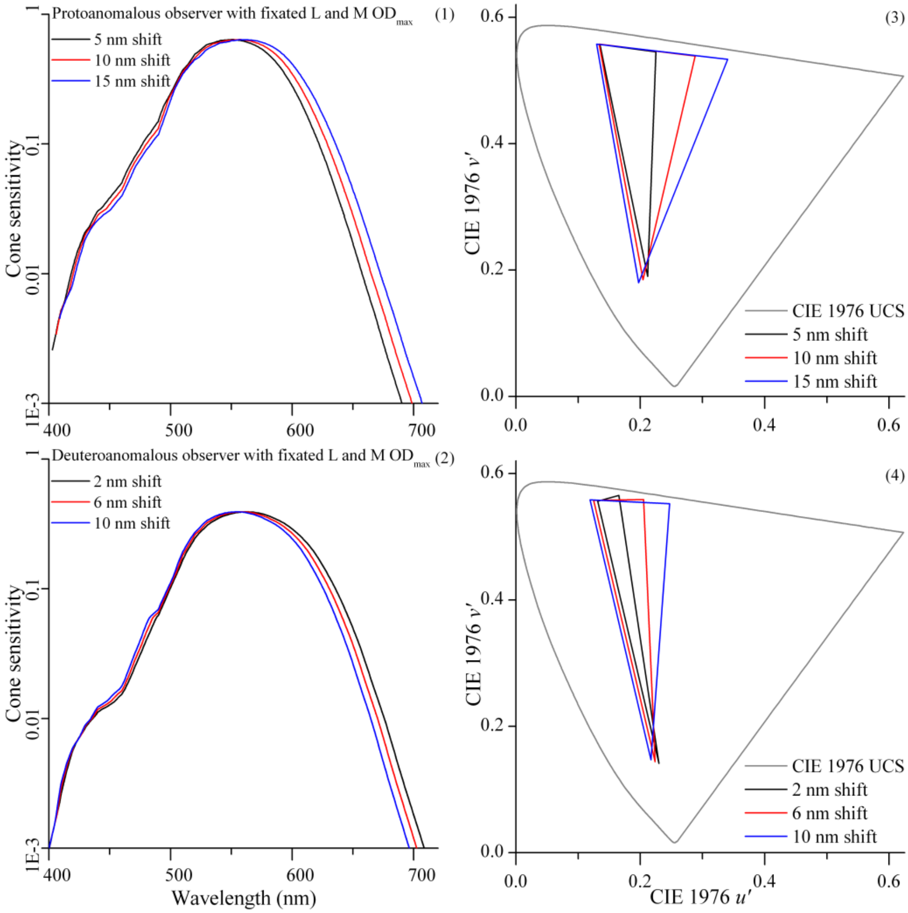

Fig. 1. Protoanomalous and deuteroanomalous spectral sensitivity curves obtained assuming the conditions described in (c) as (1) and in (f) as (2), respectively. (3) and (4) represent the corresponding display color gamut assuming the same conditions. For easier reading only the extreme (blue and black lines) and the middle (red line) of the conditions tested are represented.

3 Results

Figure 1 represents as an example of the estimated spectral sensitivity curves the protoanomalous (1) and deuteroanomalous (2) spectral sensitivity curves obtained assuming the conditions described in (c) and (f), respectively. Also represented are the corresponding display color gamut for protoanomalous (3) and deuteroanomalous (4) observers. For clarity only the extreme and middle conditions are represented. Actual estimations were computed from 5 nm to 15 nm in 0.5 nm steps for protoanomalous and from 2 nm to 10 nm in 0.5 nm steps for deuteroanomalous.

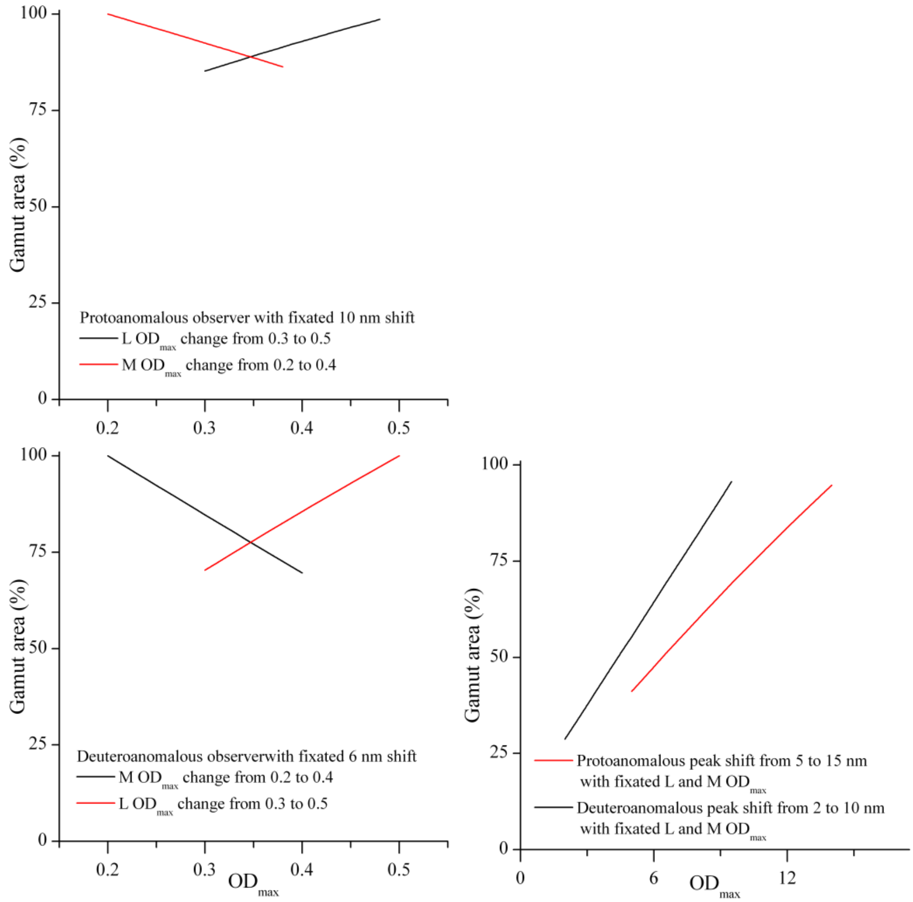

Fig. 2. Top panel represents the variations on computer color gamut area for a protoanomalous observer, assuming conditions (a) as a black line and (b) as a red line. Bottom left panel represents the same variations for the deuteroanomalous, assuming conditions (d) as a red line and (e) as a black line. Bottom right panel shows both observers and same variations as previously described varying only the peak sensitivity of the anomalous cone, assuming conditions (c) as a red line and (f) as a black line.

Figure 2 represents the estimated variations in display color gamut area for all the conditions tested from (a) to (f). The top panel represents the protoanomalous observer with fixed shifted sensitivity peak at 10 nm and independent variations on the LOD_{max} (black line) and MOD_{max} (red line), normalized to its maximum. It was found that the maximum variation of the display color gamut between extreme conditions was of 15% in both cases. Bottom left panel represents the deuteroanomalous observer with fixed shifted peak sensitivity at 6 nm and independent variations on the MOD_{max} (black line) and LOD_{max} (red line), normalized to its maximum. It was found that the maximum variation between extreme conditions was of 30% in both cases.

The bottom right panel represents the protoanomalous (black line) and deuteroanomalous (red line) observers with fixed MOD_{max} and LOD_{max} and varying the shifted peak sensitivity as described in condition (c) and (f), respectively. It was found that the maximum variation between the extreme conditions was of 59% for the protoanomalous observer and of 71% for the deuteroanomalous observer.

4 Discussion and Conclusions

As observed elsewhere [8], [12], varying the optical densities or the position of the maximum spectral sensitivity of the anomalous cone can impact the perceived color vision simulations. The results presented here show that such findings can be express in terms of a display color gamut and estimated in terms of its occupied area. The same magnitude of variations on LOD_{max} or MOD_{max} seems to affect more deuteroanomalous rather than protoanomalous observers. Despite these variations the major effect comes from varying the peak of maximum spectral sensitivity, affecting more the deuteroanomalous observers. Such effects on deuteroanomalous observers might be explained by the higher proximity of the normal L cone and the anomalous M' cone (only 6 nm apart, in average) than in protoanomalous observers where the normal M cone and the anomalous L' cone are separated by 10 nm in average. All computations assumed that the estimated display gamut represented for a normal observer the color gamut perceived by the anomalous observer.

The data presented here are consistent with those presented elsewhere [12] with chromatic diversity increasing with increase OD_{max} variations and decreasing with increasing OD_{max} in protoanomalous and deuteranomalous observers, repectively.

These results seem to indicate that the simulation of deuteroanomalous observers color vision might have a greater impact if the tested assumptions are not carefully adjusted.

Acknowledgments. This work was supported by the Centro de Física of Minho University, by FEDER through the COMPETE Program and by the Portuguese Foundation for Science and Technology (FCT) in the framework of the project PTDC/MHC-PCN/4731/2012.

References

1. Linhares, J.M., Pinto, P.D., Nascimento, S.M.: The number of discernible colors in natural scenes. J. Opt. Soc. Am. A Opt. Image Sci. Vis. **25**(12), 2918–2924 (2008)
2. Wyszecki, G., Stiles, W.S.: Color Science: Concepts and Methods, Quantitative Data and Formulae. 2nd edn. John Wiley & Sons, New York (1982)

3. DeMarco, P., Pokorny, J., Smith, V.C.: Full-Spectrum Cone Sensitivity Functions for X-Chromosome-Linked Anomalous Trichromates **9(9),** 1465–1476 (1992)
4. Merbs, S.L., Nathans, J.: Absorption spectra of the hybrid pigments responsible for anomalous color vision. Science (80-.) **258**(5081), 464–466 (1992)
5. Perales, E., Martínez-Verdú, F.M., Linhares, J.M.M., Nascimento, S.M.C.: Number of discernible colors for color-deficient observers estimated from the MacAdam limits. J. Opt. Soc. Am. A **27**(10), 2106 (2010)
6. Linhares, J.M.M., Felgueiras, P.E.R., Pinto, P.D., Nascimento, S.M.C.: Colour rendering of indoor lighting with CIE illuminants and white LEDs for normal and colour deficient observers. Ophthalmic Physiol. Opt. **30**(5), 618–625 (2010)
7. Cole, B.L.: The handicap of abnormal colour vision. Clin. Exp. Optom. **87**(4–5), 258–275 (2004)
8. Webster, M.A., Juricevic, I., McDermott, K.C.: Simulations of adaptation and color appearance in observers with varying spectral sensitivity. Ophthalmic Physiol. Opt. **30**(5), 602–610 (2010)
9. Baraas, R.C., Foster, D.H., Amano, K., Nascimento, S.M.C.: Anomalous trichromats' judgments of surface color in natural scenes under different daylights. Vis. Neurosci. **23**(3–4), 629–635 (2006)
10. Kovacs, G., Kucsera, I., Abraham, G., Wenzel, K.: Enhancing color representation for anomalous trichromats on CRT monitors. Color Res. Appl. **26**, S273–S276 (2001)
11. Machado, G.M., Oliveira, M.M., Fernandes, L.A.F.: A Physiologically-based Model for Simulation of Color Vision Deficiency. IEEE Trans. Vis. Comput. Graph. **15**(6), 1291–1298 (2009)
12. Thomas, P.B.M., Formankiewicz, M.A., Mollon, J.D.: The effect of photopigment optical density on the color vision of the anomalous trichromat. Vision Res. **51**(20), 2224–2233 (2011)
13. Barbur, J.L., Rodriguez-Carmona, M., Harlow, J.A., Mancuso, K., Neitz, J., Neitz, M.: A study of unusual Rayleigh matches in deutan deficiency. Vis. Neurosci. **25**(3), 507–516 (2008)
14. CIE, Colorimetry, CIE Publ. 15:2004. CIE, Viena (2004)
15. Brainard, D.H., Stockman, A.: Colorimetry. In: Bass, M., DeCusatis, C., Enoch, J., Lakshminarayanan, V., Li, G., MacDonald, C., Mahajan, V., Van Stryland, E. (eds.) Handbook of Optics, Volume III: Vision and Vision Optics, 3rd edn, p. 10.1. The McGraw-Hill Companies, New York (2010)
16. Knowles, A., Dartnall, H.J.A.: The characterization of visual pigments by absorption spectroscopy. In: Davson, H. (ed.) The Eye, 2nd edn, vol. 2B. Academic Press, Michigan (1997)
17. Barber, C.B., Dobkin, D.P., Huhdanpaa, H.: The Quickhull Algorithm for Convex Hulls. ACM Trans. Math. Softw. **22**(4), 469–483 (1996)