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CHROMATIC DISCRIMINATION TOWARDS THE CONFUSION POINTS

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Abstract

In this paper chromatic discrimination thresholds of normal colour-observers are analysed. Measurements were obtained with the Cambridge Colour Test, in different reference points. The results show differences in terms of the reference chromaticities. Reference points within the gamut of a CRT display were found where thresholds of normal colour observers measured towards the confusion points exceeded the normative upper threshold limit of normal colour observers. The discrimination thresholds estimated towards the confusion lines based on Trivector measurements exceeded the thresholds estimated by the Ellipse tests. Our results indicate that in case of determination of discrimination ellipses, measurements towards the confusion points are recommended.

Keywords: *chromatic discrimination, confusion point, just noticeable difference, Cambridge Colour Test.*

1. Introduction

A fundamental topic of colour vision assessment is the analysis of chromatic discrimination, which can indicate inherited defects in colour vision, such as anomalous trichromacy **[1]**, early stage of diseases, such as diabetes **[2]**, harmful environmental effects **[3, 4]** or changes in terms of age **[5]**.

Nevertheless, measurement and analysis of chromatic discrimination are important steps on the scientific road towards the colour differences and the uniform colour spaces, and their verification **[6–8]**.

The measurement method and the experimental design naturally needs to be in accordance with the objective of the actual research. Therefore, during the decades of the history of colour science several methods has been developed and applied for various clinical and investigational aims **[9, 10]**.

One of the most striking beauties of research into colour vision is, ironically, its difficulty; specifically, that colours do not exist without the observer. The human visual system is an elemental part of a system of measurement aiming to study colour perception and cognition, hence minimizing human error is a great challenge in all measurement methods.

For that reason, although in the literature there are studies about definition and comparison of large colour differences **[11, 12]**, the unit of chromatic discrimination measurements is most usually the just noticeable difference (JND), hence the smallest colour difference which the observer still can perceive.

Several JND measurement methods can be found in literature. In the case of colour matching, the task is most usually to create a colour stimulus as the additive mixture of predefined primary colours matching a target colour, both displayed in separate fields of an aperture. In this case the main parameters are the reference colour stimulus and the primary colours of the mixing light. For colour matching examination a practical example is the anomaloscope, but even MacAdam used this method in his experiment which provides a fundamental database of chromatic discrimination ellipses (known as MacAdam ellipses), which are still widely used as reference in colorimetry **[13]**.

Another prevalent method is colour ranking, where the task is to rank the coloured samples based on one or more colorimetric parameters (most often the chromaticity). In this case the perceptible difference between the successive samples is the main parameter, which can be defined as brightness, saturation, chromaticity, or any combination of these. For this test method two prevalent examples are the FM100HUE and the D15 tests but colour ranking tests are recommended as standard for the validation of normal colour vision of sensory assessors as well [14].

In clinical practice pseudo-isochromatic tests are often used. The main concept in these tests is the design of the test figures, built of randomly sized and positioned dots. Within the figure, the dots can be grouped as target and background, based on their chromaticity, while the lightness of the dots is randomised. The task is to read the target, which is possible only if the perceptible difference between the target and the background chromaticity exceeds the JND of the observer. The most prevalent pseudo-isochromatic test is the Ishihara test [15]. which is designed especially for the detection of two kinds of anomalous trichromacy: deuteranomaly and protanomaly. The main concept of the method is that the chromaticities of the backgrounds and the targets of the test images lie along the Protan or the Deutan confusion lines, therefore anomalous trichromat observers cannot, or hardly can, discriminate them.

Another pseudo-isochromatic test, prevalent in colour vision research is the Cambridge Colour Test (CCT). The advantage of CCT compared to the Ishihara test is that CCT is a computer-based test, so that experimental design can be created beyond the assessment of anomalous trichromacy [16, 17]. The task is to read a Landolt C character from the test figures (see Figure 1) and to give its orientation using a remote control. The main parameters of the test are the chromaticities of the background (reference chromaticity) and the Landolt C figure, as well as the range of luminance noise appearing in the figures.

The test is adaptive, the colour difference between the reference chromaticity (unchanged during the test) and the chromaticity of the Landolt C character is continuously increased or decreased based on the subject's responses. This adaptability, as well as the use of a calibrated CRT monitor and the ViSaGe MkII colour stimulus generator, make it possible not only to examine subjects with defective colour vision, but also to detect differences in the colour vision of normal colour observers.

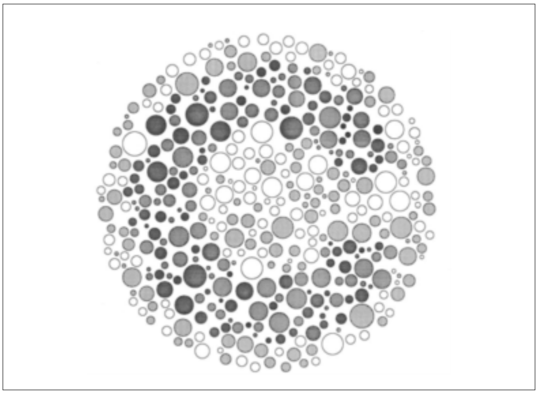

Figure 1. *The structure of a test figure of the Cambridge Colour Test. Darker dots indicate the pattern to be detected, lighter dots indicate the background. In reality, these two areas of the pseudo-isochromatic figure differ in chromaticity instead of lightness* [18].

The native colour system of the test is the CIE 1976 UCS colour chart, so it gives the chromaticity coordinates as (u';v') coordinates and the thresholds resulting from the measurement as $\Delta E_{u'v'}$ colour differences.

The two test modules of CCT are the Ellipse Test and the Trivector Test. In the case of the Ellipse test, the thresholds are determined in the measurement directions taken in equidistant directions from the reference point, and then, knowing the threshold values and the reference point, the program fits an ellipse using the least squares method to estimate the area within which the observer cannot perceive difference.

The Trivector test gives thresholds from the reference points towards the three confusion directions. Confusion directions are directions from any chromaticity point to one of the three confusion points on the CIE 1931 or 1976 UCS colour diagram. Figure 2. shows the confusion directions to the Protan (0.6579; 0.5013), Deutan (1.2174; 0.7826), and Tritan (0.2573; 0.0000) confusion points in the CIE 1976 UCS colour chart.

According to the official guidelines of the CCT [17] in the Trivector test we can talk about defective colour vision for a threshold value exceeding $100 \cdot 10^{-4}$. $\Delta E_{u'v'}$ in the Protan and Deutan confusion directions, and $150 \cdot 10^{-4}$. $\Delta E_{u'v'}$ in the Tritan confusion direction. When evaluating the Ellipse test, colour vision is typically considered normal for an axis ratio below 2.0. The limit values of the normative lower and upper Trivector test results

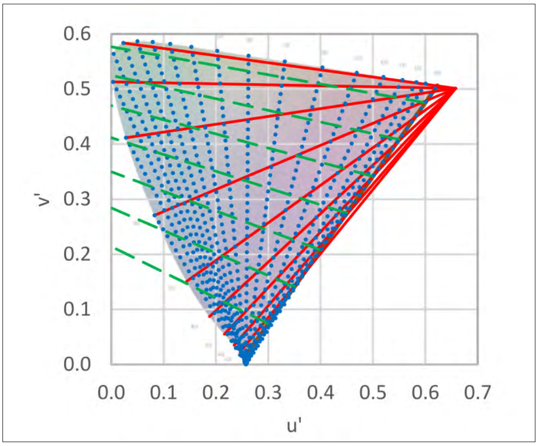

Figure 2. *Protan (solid red lines), Deutan (dashed green lines), and Tritan (dotted blue lines) confusion directions, plotted in the CIE 1976 UCS colour chart.*

determined in the literature [19] in the case of normal colour observers measured at the reference point (0.197; 0.469) are the following:

Protan: $25.2\cdot10^{-4}$; $69.3\cdot10^{-4}$;

Deutan: $24.7\cdot10^{-4}$; $82.4\cdot10^{-4}$;

Tritan: $37.3\cdot10^{-4}$; $113.4\cdot10^{-4}$.

The normative values for the Ellipse test in the following 3 reference points are known for normal colour observers. Field 1: (0.197; 0.469), Field 2: (0.193; 0.509), and Field 3: (0.204; 0.416). Normative values are given as the length of the major axis and the ratio of major to minor axes:

Field 1: $127.7\cdot10^{-4} \pm 35.8\cdot10^{-4}$; 1.6 ± 0.3;

Field 2: $142.1\cdot10^{-4} \pm 38.7\cdot10^{-4}$; 1.6 ± 0.4;

Field 3: $174.9\cdot10^{-4} \pm 47.7\cdot10^{-4}$; 2.2 ± 0.5.

While the purpose of CCT measurements in the literature is typically to compare different groups at the reference points given in the CCT manual [5, 20, 21], little data can be found on the threshold values at reference points that are very different from neutral grey. A study published by the authors of this paper [22] based on a series of Trivector tests performed in a reference point grid covering the entire gamut of a CRT monitor, shows that as the reference points are shifted from the neutral point in a confusion direction, the threshold measured from the shifted reference point in the above confusion direction increases greatly, and this increase can be estimated by a mathematical model.

The aim of our research presented in this paper is to investigate whether the increase in threshold measured towards the confusion directions can also be detected in the case of ellipse tests.

2. Methods

The measurements were performed binocularly by university students with normal colour vision in a darkened room where only the monitor displaying the test was visible. In the test figures, a luminance density of 5±3 cd/m^2 ensured that only a chromatic difference could be detected, and no decisions were made based on luminance difference.

The experimental design is in line with previous research [22]: the neutral point was defined as (0.2024; 0.4689), the reference points were shifted from this point along 8 equally distributed directions.

In the experimental design the following definitions were used: the reference direction is the direction of reference points from the neutral point to the reference point (denoted by: δ); the measurement direction is the direction in which the colour of the Landolt C character changes with respect to the reference point; and ϑ indicates the direction of the major axis of the ellipses. The directions are in each case relative to the u' abscissa.

The reference directions are denoted in the form *(k)* where $k=\delta/(\pi/4)$. The reference points are denoted along the reference directions as a function of reference distances. The reference distance increases along the arrows in the lower right corner of **Figure 3** so that the neutral point is set to 0 along each reference direction. Its unit is $\Delta E_{u'v'}=0.027$. **Figure 3** denotes the reference points -5, (3) and 3, (3) along the reference direction (3).

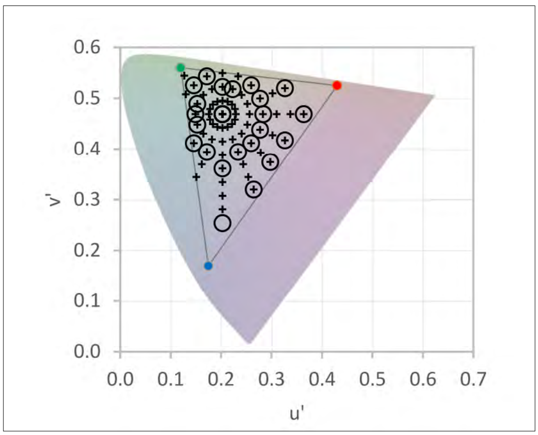

Figure 3. *Reference directions and reference points for the Trivector tests (+) and the Ellipse tests (o) in the CIE 1976 UCS colour chart.*

While the previous Trivector tests were performed in equal steps at a total of 66 reference points, the Ellipse tests were performed at a total of 23 points. Ellipse reference points were also distributed along the gamut of the display. The reference points of both experiments are shown in **Figure 3.**

3. Results and evaluation

Ellipse tests were performed with 8 measurement directions. Although the CCT gives the parameters of an ellipse fitted to the measured thresholds as a result of each measurement, ellipses fitted to the mean values of the thresholds measured per reference point were examined by the method of least squares during the evaluation. The resulting colour discrimination ellipses are shown in **Figure 4.** The ellipses are shown at 3× magnification.

A detailed evaluation of Trivector tests can be found in the authors' previous publication **[22]**. The result used in the present research is the estimation of the threshold values (Δ) measured towards the confusion directions with quadratic polynomials as a function of the reference direction and the reference distance based on (1), (2) and **Table 1.** where x is the reference distance.

$$\Delta_{P,D,T} = c_2 \cdot x^2 + c_0 \tag{1}$$

$$c_2(\delta) = \sqrt{\frac{a^2 \cdot b^2}{a^2 \cdot \sin^2(\delta - \vartheta) + b^2 \cdot \cos^2(\delta - \vartheta)}} \tag{2}$$

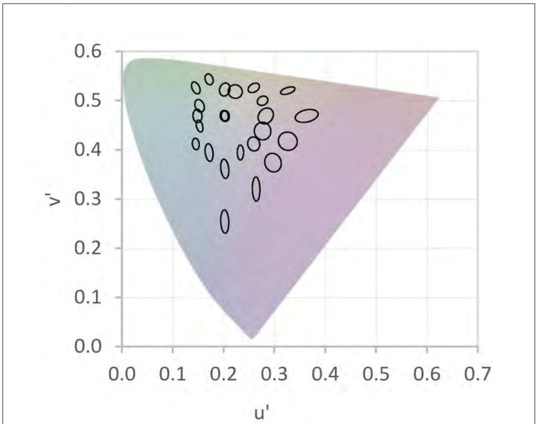

Figure 4. *Chromatic discrimination ellipses in the CIE 1976 UCS colour chart. The ellipses are shown at 3x magnification.*

Table 1. *Parameters of equations (1) and (2).* **[22]**

	Protan	Deutan	Tritan
a	2.3810	2.1872	4.6203
b	0.5549	0.7265	0.5507
ϑ	171.84°	170.62°	95.57°
c_0	31.4695	31.0190	50.2427

In the confusion directions, the threshold values estimated from equations (1) and (2) and **Table 1** determined from the Trivector measurements, and the corresponding radii of the ellipses obtained as a result of the Ellipse test measurements are shown in **Figures 5** and **6.** In the figures, the hatched dots indicate the Trivector and the filled dots indicate the Ellipse results for the Protan (●) Deutan (♦) and Tritan (▴) confusion directions, respectively. On all three graphs, the abscissa is the reference distance, and the ordinate is the chromatic discrimination threshold.

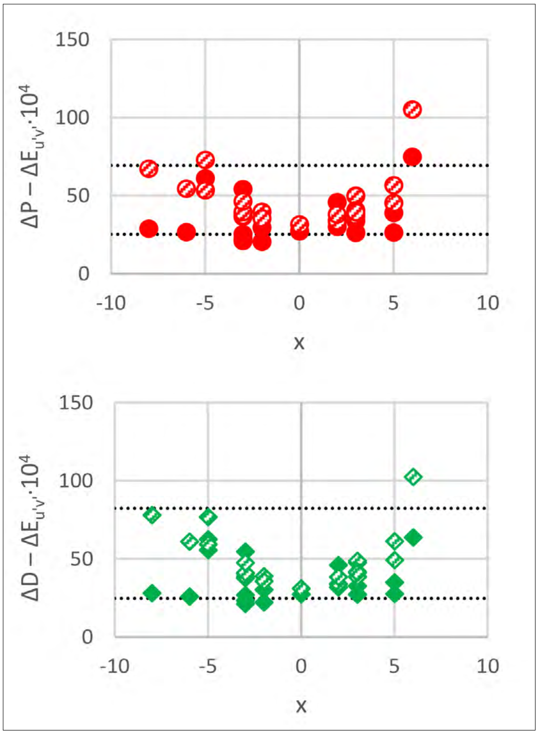

Figure 5. *Estimated chromatic discrimination thresholds (ΔP and ΔD) along the Protan (top) and Deutan (bottom) confusion directions based on the results of the Trivector (hatched) and Ellipse (filled) tests as a function of the reference distance. The dashed lines indicate the expected range of thresholds published in the literature.*

The direction of the major axes shows a strong, linear correlation with the reference direction (Spearman correlation coefficient: 0.82; p = 1.73E-06, see Figure 7), so the colour discrimination ability typically deteriorated along the reference colours of the measurements.

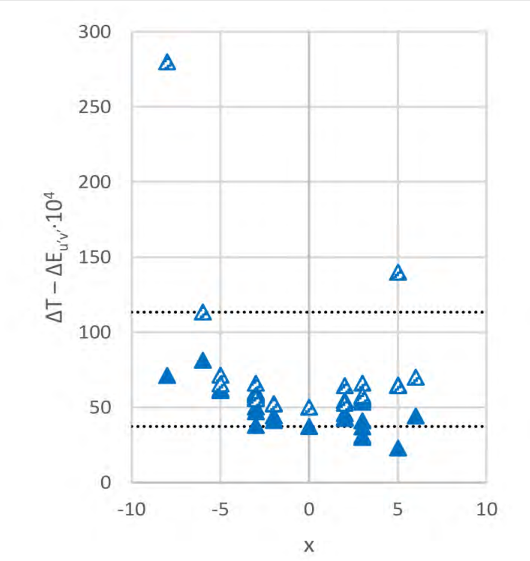

Figure 6. *Estimated chromatic discrimination thresholds (ΔT) along the Tritan confusion directions based on the results of the Trivector (hatched) and Ellipse (filled) tests as a function of the reference distance. The dashed lines indicate the expected range of thresholds published in the literature.*

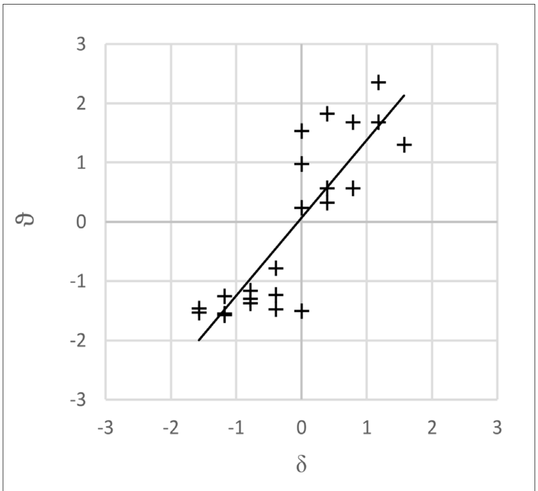

Figure 7. *Direction of the major axis of the ellipses (ϑ) as a function of the reference directions (δ).*

4. Summary, conclusion

Figures 5 and 6 illustrate that the thresholds measured in the Protan and Deutan confusion directions are similar and show a different distribution from the Tritan values for both metrics. For all three confusion directions, threshold values are seen that exceed the upper limit of the chromatic discrimination thresholds of normal colour observers.

Figure 7 and the associated correlation test show that the direction of elongation of the ellipses is strongly influenced by the direction in which the reference point is offset from the neutral colour point in the 1976 UCS diagram. However, the ellipses themselves (see Figure 4) show that the ellipses extended toward the Protan and Tritan confusion points, whereas no such direction was observed in the direction of the De-utan confusion point. This may be due to the fact that the gamut of the monitor includes a significantly narrower displayable colour range from the neutral point to the Deutan confusion direction, so we were able to display fewer reference points in the Deutan direction. To investigate this effect, further measurements are required with a display with a wider gamut.

Based on the graphs in Figures 5 and 6, the Trivector estimates exceed the threshold values calculated from the Ellipse measurements at the same reference point in almost all cases, so there were colours outside the estimated chromatic discrimination ellipses, which the subjects could not distinguish.

This suggests that the reliability of the ellipse test depends on whether one or more of the measuring directions equally splitting 360° coincide or approach one of the confusion directions. To overcome this, it is recommended to give the confusion directions a prominent role in the preparation of the experimental design, also in the case of the examination of subjects with normal colour vision.

References

[1] B. L. Cole: *Assessment of Inherited Colour Vision Defects in Clinical Practice.* Clin. Exp. Optom., 90/3. (2007)157–175.

[2] M. Gualtieri, C. Feitosa-Santana, M. Lago, M. Nishi, D. F. Ventura: *Early Visual Changes in Diabetic Patients with No Retinopathy, Measured by Color Discrimination and Electroretinography.* Psychol. Neurosci. 6/2. (2013) 227–234.

[3] D. F. Ventura et al.: *Colour Vision and Contrast Sensitivity Losses of Mercury Intoxicated Industry*

Workers in Brazil. Environ. Toxicol. Pharmacol., 19/3, (2005) 523–529.

[4] D. F. Ventura et al.: *Color Vision Loss in Patients Treated with Chloroquine.* Arq. Bras. Oftalmol., 66/5. SUPPL.(2003) 9–15.

[5] G. V Paramei, B. Oakley: *Variation of Color Discrimination across the Life Span*. J. Opt. Soc. Am. A Opt. Image Sci. Vis., 31/4, (2014) A375–A384.

[6] S. Wen: *A Color Difference Metric Based on the Chromaticity Discrimination Ellipses.* Opt. Express, 20/24. (2012) 26441.

[7] D. L. MacAdam: *Uniform Color Scales*. J Opt Soc Am, 64/12, (1974)1691–1702.

[8] Q. Xu, B. Zhao, G. Cui, and M. R. Luo: *Testing Uniform Colour Spaces Using Colour Differences of a Wide Colour Gamut*. Opt. Express, 29/5. (2021) 7778.

[9] S. J. Dain: *Clinical Colour Vision Tests.* Clin. Exp. Optom., 87/4–5. (2004) 276–293.

[10] N. Hasrod, A. Rubin: *Colour Vision: A Review of the Cambridge Colour Test and Other Colour Testing Methods.* African Vis. Eye Heal., 74/1. (2015) 1–7.

[11] M. R. Pointer, G. G. Attridge: *Some Aspects of the Visual Scaling of Large Colour Differences.* Color Res. Appl., 22/5. (1997) 298–307.

[12] S. Abasi, M. Amani Tehran, M. D. Fairchild: *Distance Metrics for Very Large Color Differences*. Color Res. Appl., 45/2. (2020) 208–223.

[13] D. L. MacAdam: *Visual Sensitivities to Color Differences in Daylight*. J. Opt. Soc. Am., 32,/5. (1942) 247–274.

[14] ISO 8586:2012 *Sensory Analysis — General Guidelines for the Selection, Training and Monitoring of Selected Assessors and Expert Sensory Assessors*. 2012. 28.

[15] S. Ishihara: *Tests for Color Blindness*. Tokyo, Kyoto: Kanehara Shuppan Co. Ltd., 1972.

[16] B. C. Regan, J. P. Reffin, J. D. Mollon: *Luminance Noise and the Rapid-Determination of Discrimination Ellipses in Color Deficiency.* Vision Res., 34/10. (1994) 1279–1299.

[17] J. D. Mollon, B. C. Regan: *Handbook of the Cambridge Colour Test*. London, UK, 2000.

[18] B. C. Regan, J. D. Mollon: *Discrimination Ellipses in the MacLeod-Boynton Diagram: Results for Normal and Colour-deficient Subjects Obtained with a CRT Display*. Drum, B. Colour Vis. Defic., XII. (1995) 445–451.

[19] D. F. Ventura et al.: *Preliminary Norms for the Cambridge Colour Test.* In: J. D. Mollon, J. Pokorny, K. Knoblauch: *Normal and Defective Colour Vision*, Eds. Oxford, 2010.

[20] G. V. Paramei: *Color Discrimination across Four Life Decades Assessed by the Cambridge Colour Test*. J. Opt. Soc. Am. A, 29/2. (2012) A290.

[21] M. F. Costa, D. F. Ventura, F. Perazzolo, M. Murakoshi, L. C. D. L. Silveira: *Absence of Binocular Summation, Eye Dominance, and Learning Effects in Color Discrimination.* Vis. Neurosci., 23/3–4. (2006) 461–469.

[22] Á. Urbin, B. V. Nagy: *Chromatic Discrimination Thresholds as a Function of Color Differences and Cone Excitations.* Period. Polytech. Mech. Eng., 65/4. (2021) 385–397.