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Multispectral Analysis of Color Vision Deficiency Tests

Sergejs FOMINS [1] *, Maris OZOLINSH [2]

[1] Optometry and Vision Science Department, University of Latvia, Kengaraga 8, LV-1063 Riga, Latvia
[2] Institute of Solid State Physics, University of Latvia, Kengaraga 8, LV-1063 Riga, Latvia

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Color deficiency tests are usually produced by means of polygraphy technologies and help to diagnose the type and severity of the color deficiencies. Due to different factors, as lighting conditions or age of the test, standard characteristics of these tests fail, thus not allowing diagnosing unambiguously the degree of different color deficiency. Multispectral camera was used to acquire the spectral images of the Ishihara and Rabkin pseudoisochromatic plates in the visible spectrum. Spectral data was converted to cone signals, and successive mathematics applied to provide a simple simulation of the test performance. Colorimetric data of the each pixel of the test image can be calculated and distribution of color coordinates is presented.
Keywords: pseudoisochromatic plates, multispectral analysis, color vision, CIE chromaticity diagram.

1. INTRODUCTION

Multispectral imaging is widely used in different fields of science. One of the most common applications to mention is astrology, agriculture, medicine and biology. In recent research it was shown how spectral data can be applied to analyze the human skin [1]. Our interest is basically related the field of human color vision. Color vision in most of vertebrates as also human species is provided by three types of photoreceptors, sensitive to blue wavelength lights (445 nm peak), green (540 nm peak) and yellow (565 nm peak) parts of the visible spectrum [2, 3]. Due to genetic reasons person could miss one, some pigments, which results in functional individualities of color perception [4]. The most common are color anomalies, than one class of the pigment is replaced by the class already represented in other cones (L or M) and could be up to 6 % of population in males [5]. Dichromacy is represented in fewer amounts in population and is around 2 % [5]. Where are different techniques for diagnostics of color vision deficiency and anomaly: anomaloscopes, arrangement tests (Farnsworth D-15, D-100), pseudoisochromatic plates. Most popular and easily applicable are pseudoisochromatic screening test plates [5]. In the last decade many research evaluating the quality and performance of the color deficiency tests being made. Color vision test performance can be evaluated either in clinical trials or by objective spectral and colorimetric measurement of the color used in the tests [5–8]. Spectroscopic data are transformed into color coordinates and conformity to dichromate confusion lines is evaluated [9, 10]. Usually both of the analyses are necessary when the novel test is introduced [11]. It has been shown [9] that different test books have significant variations, so the printing technology and the age of the test should be taken into account. To our mind, evaluation of the pseudoisochromatic tests can benefit from the use of multispectral imaging. The spectral data of the test can be acquired on the whole spatial scale, which cannot be obtained in spectroscopic or colorimetric measurement. The advantages of multispectral analysis could be a possibility to apply the higher mathematical apparatus in two dimensions over the test surface at any spectral channel of the obtained visible spectra.

In the context of this work we show the possibilities of multispectral imaging to be used for analysis of the performance of the tests and extended spectroscopic evaluation as additional tool to the accepted clinical validity testing [8].

1.1. Pseudoisochromatic plates

Pseudoisochromatic (PIC) plates are example of color camouflage. The object and background of the test design are colored spots or patches of randomly aligned size and luminance [5]. This particular properties provide size and luminance noise, so only color information can be used by individual to detect the latent object. The colors of the background and test spots are aligned along the dichromate confusion lines, with variations of luminance and chromatic saturation.

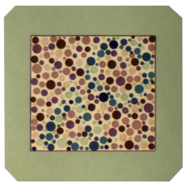

Fig. 1. Representation of the Rabkin color deficiency plate No 20 under the halogen light source. The figures (circle and triangle) are concealed in cases of protan and deuteran deficiency or anomaly (in color on line)

11th edition of the Rabkin polychromatic tables were available for our research. Rabkin tables are applied for the diagnostics of protanope and deuteranope deficiencies and their anomalies. The main group of tables 1st to 27th is for differentiation of forms of deficiency and their severity (three levels) and the second group is to double check the simulation and aggravation running the test. Anomalous deficiency can be identified in three levels of severity. In the present work we make our analysis on the plate

*Corresponding author. Tel.: +371-67-260796; fax: +371-67-132778.
E-mail address: *sergejs.fomins@gmail.com* (S. Fomins)

seventeen of the Rabkin test, which helps to discern between protanomaly and deuteranomaly within three levels of severity [12].

Another test designed by Japanese doctor Shinobu Ishihara in the beginning of the XX century is the one of most popular and widely used printed tests was used for analysis together with Rabkin test [9]. Both of these two tests use the same "vanishing" design, when latent object is concealed for individuals with anomaly or deficiency.

2. EXPERIMENTAL DETAILS

Spectral images of the tests were acquired with CRI Nuance II Vis 07 spectral imaging system with Nikon AF Micro-Nikkor 60mm f2.8D objective mounted. Spectral images were taken in the range of 420 nm to 720 nm with the 10 nm step. For the illumination of the test, ordinary 12 V 35 W halogen bulb without filter was used. There are no specific lighting indications for Rabkin test [12]. The Ishihara pseudoisochromatic test contains considerations for daylight lit illumination [13]. In our geographic area it could be not easy to find the daylight adequately lit room in winter time. For this reason, we suggest, that in many cases screening take place in different illumination conditions and the most used is a typical halogen bulb light source. The halogen bulb irradiance spectrum was measured with Ocean Optics USB4000-VIS-NIR spectrometer through the calibrated Ocean Optics optical fiber. The color temperature of the lamp is around 4000 K and it has continuous spectra (Fig. 2).

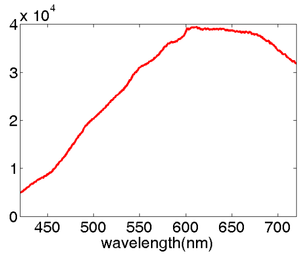

Fig. 2. Halogen bulb (12 V, 35 W) irradiance spectrum

A semi gloss paper is used for Rabkin test and as a result it produces the glare and smudges with the straight lighting. To avoid the glare and reflections from the paper surface, 45/0 illumination geometry was chosen [14]. The spectral camera was placed just in front of the test and the halogen bulb was placed 45 degrees to the test plane. The light source was placed at 1.5 m distance to produce the homogenous illumination of the measured pseudoisochromatic plate's surface.

3. ANALYSIS

In case of color dichromacy subjects are missing long wavelength sensitive (LWS or L cones in case of protanopy) or middle wavelength sensitive receptors (MWS or M in the case of deuteranopy). Multispectral data provide an easy background for simulation of the deficiencies, due to the possibility to apply the cone spectral sensitivity functions to each pixel of the acquired image and introduce the missing signal. In the case of anomaly the pigment of LMS and M cones differs only slightly, which results in reduced, but anyway trichromatic color vision [4, 5].

To transform the acquired multispectral images to L, M, S cone signals we have used the cone sensitivity functions (Eq. 1)

$$L(\lambda)=\sum_{420}^{720}W(\lambda)\cdot l(\lambda);\quad M(\lambda)=\sum_{420}^{720}W(\lambda)\cdot m(\lambda);$$
$$S(\lambda)=\sum_{420}^{720}W(\lambda)\cdot s(\lambda); \qquad (1)$$

where $W(\lambda)$ is the multispectral image of the Rabkin tests (consisting of 31 layer) obtained with the 10 nm step from 420 nm to 720 nm; $l(\lambda)$, $m(\lambda)$, $s(\lambda)$ are the cone spectral sensitivities by Stockmann *et al*. [2].

The 17th plate of Rabkin test is really suitable for this analysis, as it diagnose between deuter and protan with C level of severity. Dichromate and A, B level subjects would miss in this test. From the Ishihara 12th plate was chosen for analysis as it helps to identify severity of the deuter- and protan- anomalies in a way similar to Rabkin 17th plate. We were not aware of the color saturation and design details of the tests, except available information on test design [5]. The cones sensitivities used to design these tests were slightly different from used in our study, as also tests could be designed on the principles different from the modern color science [15]. Fig. 3 and Fig. 4 show different representations of the L and M signal proportions and resulting appearance of the latent object. Through the manipulations with the LMS images we have identified that the 0.85L – M case corresponds the most to the behavior of the normal color vision subject and proportional subtraction of a·0.85L – b·M can be used to simulate the anomaly ($a, b > 0$) or deficiency ($a, b = 0$) of the one of the cone signals. In our analysis we have used normalized cone sensitivities, which mean we have similar signals of L, M and S cones influenced only by our acquired multispectral data.

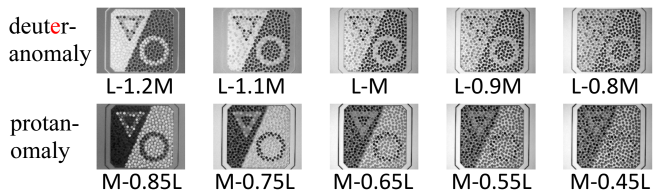

Fig. 3. Anomalous perception simulation for Rabkin plate No 17. Protanomalous perception simulation would highlight "triangle" object (bottom row) and simulation for deuteranomalous perception would make "circle" object more explicit (top row)

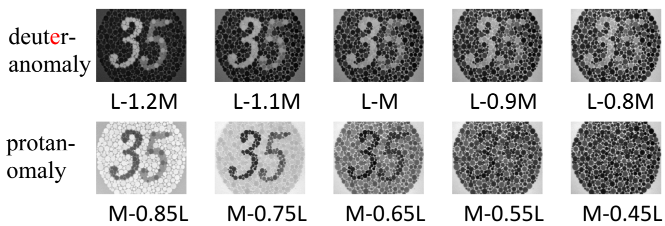

Fig. 4. Anomalous perception simulations for Ishihara plate No 12. In the case of strong protanomaly object "five" should be more prominent and in case of deuteranomaly, person would perceive object "three". In the case of mild anomalies person would see can see both numbers

In Figs. 3 and 4 a simple simulation of anomaly by manipulating the L and M signal magnitudes is introduced. The latent objects in the Fig. 3 (Rabkin test 17th plate) are separated according to the LWS or MWS cone signal changes, which is in accord with the test design. In the case of Ishihara plate No 13 (Fig. 4) latent objects are present for deuteranomaly simulation and almost invisible for protanomaly simulation. However, the test shows the right tendency for object "three" to be present for deuteranope deficiency and to disappear for protanope deficiency. It is necessary to remark, that Ishihara`s PIC tests are designed to be used in lit daylight illumination.

3.1. Distribution of color coordinates in CIE chromaticity diagram

To obtain the coordinates for chromaticity diagram color matching functions are necessary as defined by CIE (Commission Internationale de l'éclairage) or International Commission of Illumination. For our purposes we have used CIE defined color matching functions for 10 degree observer (1964), because measured test`s surface subtends more than 2 degrees of visual angle in vertical and horizontal directions [14 – 16].

In the pseudoisochromatic plates colors of the hidden objects and background are supposed to be arranged along the dichromate confusion lines. Multispectral analysis of the tests helps to gather the spectra of the each point of the image and allows calculation of CIE x, y coordinates each particular pixel. Two-dimensional histogram of the CIE x, y coordinates can be calculated, as shown in Fig. 5 and Fig. 6. The latent objects of the Rabkin plate No 17 are separated to decrease the confusion of coordinates and to make the interpretation easier. The lines in the figures show the direction of the dichromate confusion lines.

Confusion lines represent the series of narrow zones in the CIE x, y with identically perceived colors for dichromatic vision. Colors along the isochromatic lines look the same if no luminance difference is introduced between two colors. Isochromatic data for anomalous trichromats are similar to those of the corresponding dichromats, but do not include the complete range of chromaticities [5]. For this reason highly saturated colors can be perceived by anomalous vision, and small color changes should be used for classification of the severity of color anomaly. Dichromatic convergence points for isochromatic confusion lines are given for all three types of deficiencies (see Table 1) [5, 17].

In Fig. 5 (top) the biggest spot corresponds for the yellow background, as it subtends the large area of the test. The green spots (of the "triangle" object) are arranged horizontally over the background spot and background red spots are on the right of the background. There are four spots which align along protanope confusion lines or deuteranope confusion lines. For protanopic latent object ("circle") the top right spot is not on the confusion lines. For the deuteranope stimuli top left spot do not have any spot to be aligned with on the confusion line. In such way these two spots are seen in the case of dichromacy. Spots aligned on the confusion lines are arranged in different distances from each other and in such way this design makes the diagnostics of the severity possible.

Table 1. Copunctal points of dichromate confusion lines

Deficiency (anomaly) type	x	y
Protanopic (red lines)	0.7465	0.2535
Deuteranopic (green lines)	1.40	–0.40
Tritanopic	0.1748	0.00

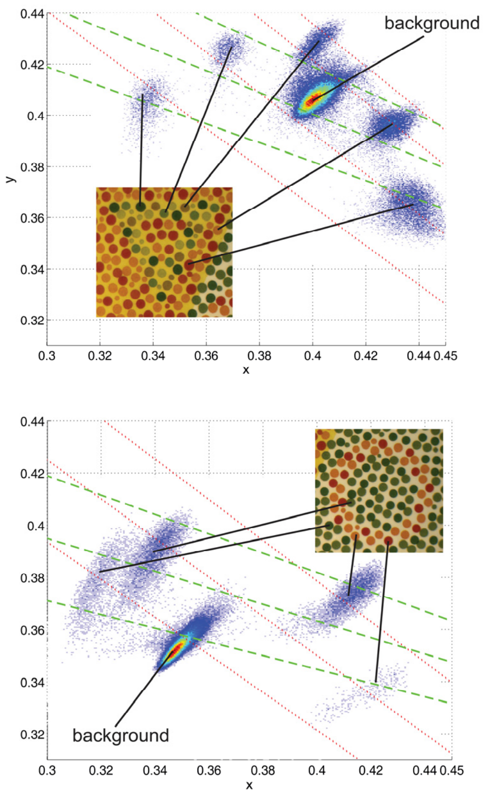

Fig. 5. CIE x, y coordinates distribution for plate No 17 of Rabkin test. Top figure is the 'triangle' object (seen by protanope) and bottom figure is for the 'circle' object of the test (seen by deuteranope). Red solid lines represent deuteranope confusion lines with starting point in coordinate $x = 1.40$; $y = –0.40$. Green dashed lines show confusion lines for the protanope with coordinates at $x = 0.7465$; $y = 0.2535$ [17] (in color on line)

The same logic can be applied for analysis of Ishihara plate (Fig. 6). However, in this case arrangement of the spots is not that obvious, especially for the object "five" (Fig. 6, bottom). The influence of chromaticity coordinates on test performance can be clearly seen in our simulation in Fig. 4 for particular plate. As the spots of both objects are aligned along the protanope confusion lines (green lines), decrease of L signal is producing pronounced vanishing of objects in simulated images. Almost all of the spots of object "five" are aligned along deuteranope confusion lines (Fig. 6, bottom), which makes the latent object to disappear when M cone signal is decreased.

3.2. Hue dispersion

Conversion of the spectral data to the CIE x,y chromaticity diagram coordinates can be used to analyze the hue dispersion in the test. As we can see from Figs. 5 and 6 the Ishihara test shows wider dispersion of the color coordinates, for both – background and test stimuli. However, no extension along some axis is present in the Ishihara plate No 12. The dispersion can be characterized with the

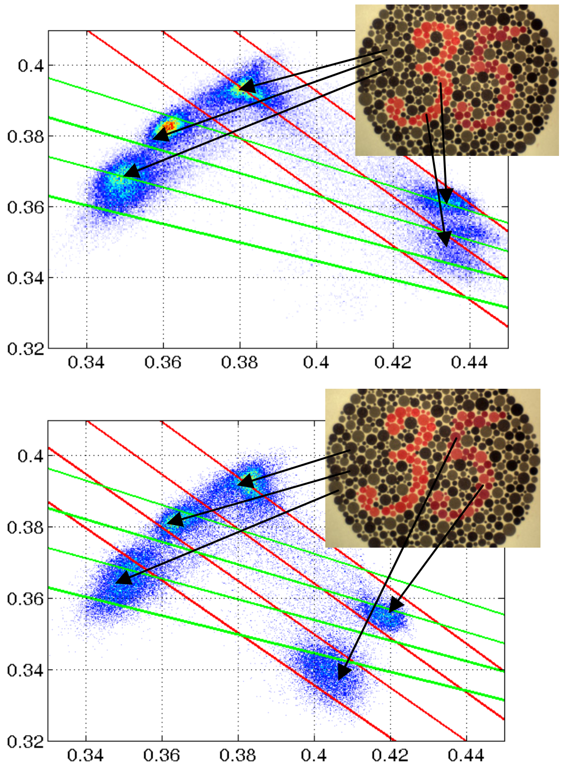

Fig. 6. CIE x,y coordinates distribution in plate No 12 of Ishihara test. Top figure is for the "three" object and bottom figure is for the "five" object. Red solid lines represent confusion lines for the deuteranope with copunctal point in $x = 1.40$; $y = -0.40$. Green dashed lines show confusion lines for the protanope with coordinates at $x = 0.7465$, $y = 0.2535$ [17] (in color on line)

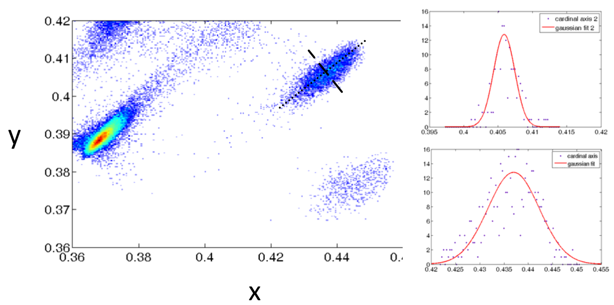

Fig. 7. Dispersion of the test hues in the CIE x, y chromaticity diagram and the Gaussian fit (two figures on the right) of the data points. X axis in the graphs on the right show the CIE x, y values. The probability is placed on the y axis

Gaussian function along two cardinal axes of the hue distribution (Eq. 2)

$$f_G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-a)^2}{2\sigma^2}}, \qquad (2)$$

where σ is a standard deviation; e is an exponent function; a is a mean value of the function.

To compare two tests we tried to find the σ (95 %) of the Gaussian fit for the dispersion. For the Rabkin test sigma values for the particular area (Fig. 7) were 0.0053 and 0.021 for cardinal axes of distribution. For Ishihara test sigma values were 0.011 for the minor axis and 0.023 for the major axis. Distributions for "triangle" object of Rabkin plate No 17 appear not elongated in diagonal direction, which can be seen for the "circle" objects colors (Fig. 5).

Our results show that, in alternative to the previous colorimetric or spectrometry studies, tests colors subtend some area in the CIE x, y chromaticity diagram. We suggest that dispersion can differ depending on the printing technology and also the age of the test. This probably can be the reason for Ishihara test to show larger dispersions. However, it is difficult to judge about particular quantity. This probably should be studied in connection with clinical data, to understand the benefits or drawbacks of chromatic dispersion on test performance.

4. RESULTS AND DISCUSSION

In the first part of analysis we have provided the algorithm for two dimensional simulations of the color deficiencies. The spectral data of each multispectral image are transformed to cone signals images. Mathematics similar to that between the cones inputs in the human retina are applied to obtain the simulations of the dichromatic perception of the color deficiency tests.

In the second part of our analysis colorimetric values of the tests are calculated and their distributions across the chromaticity diagram are given. The design of plates becomes visible from the arrangement of the colors in the CIE chromaticity diagram. Multispectral analysis provides two dimensional spatial data and makes possible calculation of the distribution of colors, which can arise to different factors as: used printing technology and dilapidation of the test. Distributions for Rabkin test show elongation of the chromaticity coordinates in the diagonal direction (from blue to yellow colors). No such elongation is observed for Ishihara test plate. We should remark, colors in Rabkin test are produced by printing technique that uses halftoning. Ishihara test is printed by solid dyes with no seen dots. However, this effect can be perceived by high magnification and observing the test closely, but the dots are not apparent in acquired multispectral images.

Colorimetric studies of the color deficiency tests usually identify variations of the color coordinates from test to test [9, 10]. If spectrometer of chromameter is used for measurements only restricted part (or integral area) of the test surface can be measured. To our mind, this can be produced by variations of the coordinates in different measurements and at different test spot locations. The distributions of color coordinates for test object colors shown in our analysis subtend area of 0.015 till 0.02 units in CIE chromaticity diagram. Due to this fact, there is some tolerance available for the alignment of the test colors on the confusion lines. On the other side, if the distributions overlap the confusion lines, too large dispersions can impact the test diagnostic abilities.

5. CONCLUSIONS

We have measured the multispectral images of two pseudoisochromatic test plates in the visible spectrum from 420 nm to 720 nm. Spectral images were converted to cone signals with successive post-processing to introduce the performance of the test for anomalous color vision. Color coordinates of the test latent objects and background were calculated and distributions of colors were found. We suppose that, color dispersions are produced by print technology, which is disclosed by elongation of chromatic dispersion.

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