UNIVERSITY OF LATVIA

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DEVELOPMENT OF PSYCHOPHYSICAL PSEUDOISOCHROMATIC TEST AND EVALUATION OF COLOR DISCRIMINATION THRESHOLD

SUMMARY OF DOCTORAL THESIS

Submitted for the degree of Doctor of Physics

Subfield of Medical Physics

Riga, 2015

University of Latvia

Faculty of Physics and Mathematics

Kaiva Juraševska

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The thesis is available at the Library of the University of Latvia, 4 Kalpaka Blvd.

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Abstract

Purpose - to create a printed psychophysical pseudoisochromatic test for the assessment of individual color discrimination thresholds in case of congenital red-green color vision deficiency; to characterize their degree of variability; anticipate color discrimination ability in case of other color vision testing systems.

A psychophysical pseudoisochromatic test was created. For assessment of the test, firstly, cone responses for both deficiency types and various deficiency levels are modeled mathematically; second, test performance is compared with the tests used in clinics - the standard in the diagnosis of color vision (anomaloscope) and Richmond HRR test. Test performance for diagnosing type and grading severity level of red-green color vision deficiency is analyzed. Individual color vision discrimination thresholds are obtained and analyzed, changes over several trials discussed, and hypothesis about visual perception in case of red-green color vision deficiency are raised.

Comparison of two printing methods for the creation purposes of the test (inkjet print and photographic print) showed smaller color coordinate dispersion in case of inkjet printing. While testing our developed method in a randomly selected school-age children population (n = 273), high diagnostic ability of the test was obtained – sensitivity and specificity (with the chosen test criterion > 1 error) were 1.0 and 0.9962 respectively; comparing our test and Richmond HRR test a moderately strong correlation between the deficiency level severity gradings was obtained. It was concluded that the designed psychophysical tests can be used to assess red–green color vision deficiencies and to obtain individual color saturation discrimination thresholds in the case of anomalous trichromates. A characteristic color discrimination threshold value in CIE LAB ΔE units was found for each mildly deuteranomalous individual tested with pseudoisochromatic plates, this threshold value did not change significantly in multiple measurements (value variation was less than 2 ΔE units). No variations of threshold value were found within the monitored time interval (one month). The obtained color discrimination thresholds strongly correlate with the results obtained in color vision tests used in clinics. A strong positive correlation (r = 0.92) exists between anomaloscope AQ and deuteranomalous color discrimination thresholds acquired by the new test, and (r = 0.92) between error scores in HRR test and thresholds acquired by the new test. A perceptual model describing acceptable shifts from theoretical confusion lines in case of red-green color vision deficiency is created.

Keywords: Color vision, Psychophysics, Visual system, Color measurement, Altered color vision, Color vision deficiency, Color perception.

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1. Introduction

Altered color vision affects approximately 8% of male and 0.4% of female population and congenital red-green color vision deficiency (M-cone dysfunction - protan deficiency and L-cone dysfunction - deutan deficiency) makes up most part of above mentioned percentage (Birch, 1993; Neitz un Neitz 2011). In case of affected M-cone or L-cone function, the deficiency most commonly manifests as a difficulty to distinguish between certain colors in red and green part of the electromagnetic radiation spectrum, which is why these types of deficiency can be grouped together under the denomination **red-green color vision deficiency.** One of the most common methods used for the detection of altered color vision are pseudoisochromatic (PIC) test plates. Regardless of the design used for the creation of pseudoisochromatic tests, they are based on evoking different grouping responses in people with normal trichromatic and abnormal color vision. Colors for such plates must be chosen in specific alignment to CIE (*Commission internationale de l'éclairage*) *xy* color diagram confusion lines according to each deficiency type (Birch, 1993; Smith and Pokorny 1975). By careful choice of colored symbol chromatic values and its corresponding background color, tests characterized by high test validity can be obtained (Cole, *et al.*, 2006; Cole, 2007). The amount of total color difference ΔE^*_{ab} of the test plate determines the level of difficulty of the specific plate. PIC tests usually **classify color-vision deficiency** in terms of severity into three groups: mild, medium (moderate), and strong (severe). For red–green color-vision deficiencies, advisable values of ΔE^*_{ab} measured by the CIE LAB formula are:

1) 15 – 22 units for small deficiency (screening);
2) 30 – 40 units for medium deficiency;
3) 50 – 60 units for severe deficiency detection (Birch, 1993).

1.1. Topicality

The perception of color in case of color vision deficiencies is still studied and tests for quantitative measurement of deficiency severity are developed (Barbur, *et al.*, 2008; Rabin, *et al.*, 2011). Studies have shown that high desired chromaticity value accuracy for PIC test creation can be obtained using calibrated inkjet printing (Luse, *et al.*, 2012). Development of new tests and search for unconventional test development methods also requires analysis of the repeatability of the print as well as evaluation of the plate color value fading dynamics. Research shows that colors from the same test plates but different editions have significant chromatic variations that result in clinical misevaluation (Lee and Honson, 2003).

The gold standard for color-vision diagnostics is the anomaloscope testing procedure. It also characterizes the abnormality by assigning a quantitative value to the examination result. Other frequently used tests are usually based on error counting that is further associated with the severity of color-vision deficiency. Although the anomaloscope is a precise instrument, it has been reported that the **correlation between matching range results and the ability to perform everyday color discrimination tasks** like judging surface colors **is poor** (Birch, 2008; Baraas, et al., 2010). Nevertheless, the anomaloscope matching range of an individual is often used as a measure of the severity of the color-vision deficiency (Birch, 1993).

It would be convenient to characterize individual color discrimination sensitivity in terms of a threshold value, such as the total color difference value in CIE LAB (a.k.a., CIE La*b*) color space, for colors on confusion lines required to perceive just noticeable difference. It has been suggested before that scoring techniques for expressing test results in terms of sensitivity loss might be informative (Smith, *et al.*, 1993).

1.2. Purpose and objectives of the study

Purpose - to create a printed psychophysical pseudoisochromatic test for the assessment of individual color discrimination thresholds in case of congenital red-green color vision deficiency; to characterize its degree of variability; anticipate color discrimination ability in case of other color vision testing systems.

Objectives of the study:

1) Create a printed psychophysical pseudoisochromatic test based on color matching experiment results. Assess the validity of the test for clinical purposes and the evaluation of color discrimination threshold.

2) Characterize the ability of the created test to subdivide and quantitatively assess individual color discrimination thresholds in case of mild degree red-green color vision deficient individuals and estimate the variability of the threshold values over time.

3) Assess the correlation of the obtained color discrimination thresholds and the results of other color vision tests.

4) Explain the changes of color discrimination ability of protans and deutans along the neutral point in CIE *xy* color diagram.

1.3. Methodology

1) Sample matching experiments in controlled illumination conditions for the creation of a new color vision test.

2) Sample colorimetric value measurements, reflectance measurements, sample analysis, multispectral snapshots, photometric measurements for modeling of visual perception in case of color fading over time.

3) Tools used in clinics for the detection and diagnostics of altered color vision – golden standard *Oculus HMC anomaloscope*. Other tests - Richmond HRR, Farnsworth D15, CAD test derivative, our developed psychophysical pseudoisochromatic test.

4) Multispectral camera and software for converting the resulting image to cone response functions, modeling of the resulting cone response to created stimuli depending on the color vision deficiency type and severity level.

1.4. Novelty of research

1) A printed psychophysical test is created which characterizes severity of the red-green color vision deficiency with a threshold value in physically measurable units – total color difference ΔE. The results given in in terms of total color difference may be useful and easy to interpret for specific applications or for product developers (results depict color-sensitivity loss in comparison with the color-discrimination ability of a normal observer for neutral colors).

2) Color matching experiments (not theoretical averaged stimuli/background color relations) were used to create the test.

3) A deeper level of understanding on the perception in case of red-green color vision deficiency has been gained individual differences and constant value of threshold over time and several trials.

1.5. Author's contribution:

Creation of color samples and the matching experiment was performed by the author and MSc A. Gūtmane. Both versions of the pseudoisochromatic psychophysical test described in the study were created by the author. The data for the test performance assessment in the population were gathered by the author with the help of MSc A. Paušus, BSc B. Zutere and PhD S. Fomins. The test plate fading analysis described in the study was performed by the author. The modeling of the cone signal responses and the acquisition of the multispectral imagery were performed by the author using the algorithms created by S. Fomins. The gathering of data by the second version of our test was performed by BSc A. Livzāne and B. Zutere. Data analysis, creation of all images and figures, interpretation of the results is an accomplishment of the author alongside thesis supervisor M. Ozoliņš. The publications the dissertation is based on were written by the author (with the counsel of the supervisor) or (in one case) teamwork of B. Zutere and author.

1.6. Defendable thesis

1) A printed psychophysical pseudoisochromatic test is created based on color matching experiments. The test can be used for quantitative assessment of individual color resolution thresholds along both sides of the neutral point in the CIE *xy* color diagram. The created test is evaluated as valid for clinical use (sensitivity 100% and specificity 99.62% (with the selected test criterion <1 error)).

2) The developed test allows to quantitatively assess an individual color resolution threshold value of mildly deuteranomalous and protanomalous observers. The color resolution thresholds in CIE LAB total color difference (ΔE) units for deuteranomalous observers are constant values over time.

3) There is no improvement in correlation between characterization of color vision deficiency levels for similar pseudoisochromatic test pair (Richmond HRR and the created test KAMS) and anomaloscope – KAMS test pair. Despite the differences in construction and operating principles of the pseudoisochromatic test and anomaloscope.

4) Matching experiment results suggest a hypothesis - an increase in stimuli saturation causes acceptable color coordinate shift decrement from the confusion line passing through the neutral point in CIE *xy* diagram for both - protan and deutan observers.

1.7. List of publications

Publications relevant to dissertation:

1) **Jurasevska K**., Ozolinsh M., Fomins S., Gutmane A., Zutere B., Pausus A., Karitans V., „Color discrimination threshold determination using pseudoisochromatic test plates", *Front. Psychol.*, doi: 10.3389/fpsyg.2014.01376 (2014).
2) Zutere B., **Jurasevska K**., Livzane A. „The stability of color discrimination threshold determined using pseudoisochromatic test plates", *Proc. SPIE 9216, Optics and Photonics for Information Processing VIII*, 92161G; doi:10.1117/12.2061748 (2014).
3) **Luse K**., Ozolinsh M., Fomins F., Gutmane A., „Multispectral analysis and cone signal modelling of pseudoisochromatic test plates", *IOP Conf. Ser.: Mater. Sci. Eng*., 49 012041 doi:10.1088/1757-899X/49/1/012041 (2013).
4) **Luse K**., Fomins S., Ozolinsh M., „Pseudoisochromatic test plate colour representation dependence on printing technology", *IOP Conf. Ser.: Mater. Sci. Eng*. Vol. 38, 012024 (2012).

Other publications:

1) **Luse K**., Ozolins M., Karitans V., „Effect of retroreflector position on the detection and recognition of pedestrian under reduced visibility", *Latvian Journal of Physics and Technical Sciences*, N4, p.40–48, (2011).
2) **Luse K**., Pausus A., Karitans V., Ozolins M., Tukisa M., "Evaluation of retro-reflective coating performance by reflectance and perceived relative brightness measurements", *IOP Conf. Ser.: Mater. Sci. Eng*. Vol. 23., 012005, (2011).
3) Karitans V., Ozolinsh M., **Luse K**., Ekimane L., „Presence of spherical aberration in the reference as a possible source of variations in magnitude of measured ocular aberrations", *Optica Applicata*, Issue 3, vol. 42, DOI: 10.5277/oa120308, pp. 519 - 532 (2012).
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5) Karitans V., Ozolinsh M., Ekimane L., **Luse K**., „Dependence of Vernier acuity on the extent of retinal blur", *Latvian Journal of Physics and Technical Sciences*, N4, pp. 49-57 (2011).

1.8. International conference thesis (selection)

1) B.Zutere, **K.Jurasevska**, A.Livzane, „The stability of color discrimination threshold determined using pseudoisochromatic test plates", Abstr.Int.Conf. Optics and Photonics for Information Processing VIII, USA, San Diego (Paper 9216-49) (2014).
2) A.Gutmane, **K.Jurashevska,** S.Fomins, „Perception and color analysis in time of printed color vision test", Abstr.Int.Conf. DOC 2014, Riga, Latvia, p.41 (2014).
3) **K.Luse**, M.Ozolinsh, S.Fomins, A.Gutmane, „Evaluation of Pseudoisochromatic Plate Colour Fading", Abstr.Int.Conf. Advanced Materials and Technologies 2013, Palanga, Lithuania, p.112. (2013).
4) **K.Luse**, M.Ozolinsh, S.Fomins, „Chromatic sensitivity variances along confusion lines for congenital red-green colour deficient individuals", Abstr.Int.Conf. ICVS 2013, Winchester, UK, p.138, (2013).
5) **K.Luse**, M.Ozolinsh, S.Fomins and A.Gutmane, "Obtaining individual chromatic sensitivity thresholds in case of congenital red-green color deficiency", Abstr.Int.Conf. AIC 2013, Gateshead, UK, p.239. (2013).
6) **K.Luse**, M.Ozolinsh, S.Fomins, A.Gutmane, B.Zutere „Individual chromatic sensitivity threshold determination in case of red-green color deficiency", Abstr.Int.Conf. DOC 2013, Riga, Latvia, p.78-79. (2013).
7) **K.Luse**, M.Ozolinsh, S.Fomins „Reflectance and multispectral evaluation of color vision asessment plates", Abstr.Int.Conf. FM&NT 2013, Tartu, Estonia, p.228. (2013).

8) B.Zutere, **K.Luse** „Usability of psychophysical experiment scheme in colour vision deficiency characterization". Abstr.Int.Conf. Open Readings 2013, Vilnius, Lithuania, p.184. (2013).
9) **K.Luse**, J.Logina, „The impact of the background on the recognition of road signs", Abstr.Int.Conf. ERNI-HSF Science Meeting Orienting of Attention, Neural Implementation, Underlying Mechanisms and Clinical Implications, Tuebingen, Germany, p.37. (2012).
10) **K.Luse**, S.Fomins, M.Ozolins, „Color representation dependence on printing technology", Abstr.Int.Conf. Functional Materials and Nano Technologies, Riga, p.171. (2012).
11) **K.Luse**, S.Fomins, „Photographic and ink printing colorimetric diference and spectral specificities", Abstr.Int.Conf. Developments in Optics and Communications, Riga, p. 60. - 61. (2012).
12) **K.Luse**, M.Ozolins, S.Fomins, „Colour discrimination threshold determination using pseudoisochromatic test plates obtained by photographic and inkjet printing", Abstr.Int.Conf. European Conference on Visual Perception 2012, Great Britain, *Perception* Vol.41 supplement, p.85. (2012).
13) **K.Luse**, S.Fomins, M.Ozolinsh, „Printed test plates for color discrimination treshold determination", Abstr.Int.Conf. 6th EOS Topical Meeting on Visual and Physiological Optics, Dublin, Ireland, p.87. (2012).
14) **K.Luse,** A.Pausus, M.Ozoliņš, V.Karitans, „Evaluation of Commercial Retroreflector Optical Properties", Abstr.Int.Conf. The 13-th International Conference-School „Advanced Materials and Technologies", Palanga, Lietuva, p.38. (2011).

2. Literature review

2.1. Red-green color vision deficiency

Congenital color vision deficiency covers a wide range of hereditary, stationary conditions in which there is an abnormality of color matching and/or color discrimination. Usually other visual function (such as visual acuity) remains unaltered. Today it is recognized that congenital color-vision deficiencies (CVD) are caused by point mutations, rearrangements, and deletions of the opsin genes that are responsible for determining the structure and function of the visual cone photopigments. Congenital CVDs can be characterized from two different standpoints – a qualitative dimension (how the visual function is altered), and a quantitative dimension (the severity level of the CVD). (Shevel, 2003; Birch, 1993) Hence forward only the most commonly found CVD types are analyzed – red-green CVDs (protan and deutan defects).

There are two qualitatively different forms of X-chromosome linked congenital deficiency. **Protan observers** show normal spectral sensitivity in middle wavelength part of the spectrum (L-cone or long wavelength sensitive cone function is impaired). **Deutan observers** show normal spectral sensitivity in long wavelength part of the spectrum (M-cone or middle wavelength sensitive cone function is impaired). The protan and deutan defects include, firstly, dichromatic cases – protanopia and deuteranopia (the affected observer will require only two primaries for matching any color), and, secondly, anomalous thrichromacy – protanomaly and deuteranomaly. Color matching results for protanomalous and deuteranomalous observers differ one from another and those in the case of normal trihromatic vision. The increment of color discrimination ability significantly differs. In case of dichromatism, the color discrimination ability is significantly lower than in case of anomalous thrichromacy. Color confision and spectral sensitivity in groups "protanomalous and protanope", and "deuteranomalous and deuteranope" individuals are qualitatively similar which explain the connecting titles "protans" and "deutans". (Shevel, 2003; Birch, 1993)

2.2. Confusion lines in CIE *xy* color diagram

The assumption that protanopes and deuteranopes lack one of the normal cone functions allows representing dichromatic color matches in trichromatic color vision diagrams (see Figure 1). By finding two colors indistinguishable one from another and connecting the corresponding chromatic values in color diagram allows the formation of a series of lines (called the *confusion*, *isochromatic* and *pseudo-isochromatic* lines hinting that the colors (corresponding the points on the lines) are in fact different, but the individual

with corresponding deficiency cannot tell them apart). In the CIE *xy* color diagram the confusion lines converge to a confocal point (specific for each type of deficiency). In cases of protanopia and tritanopia (lack of S-cone function) the locations of the confocal points correspond to visual spectrum endpoints on the outer curve. (Shevel, 2003)

Each type of CVD has one specific confusion line that passes through the achromatic point in the CIE *xy* color diagram. Colors on these lines are called the *neutral colors* and the intersection of this point – the *neutral point*. (Shevel, 2003; Birch 1993).

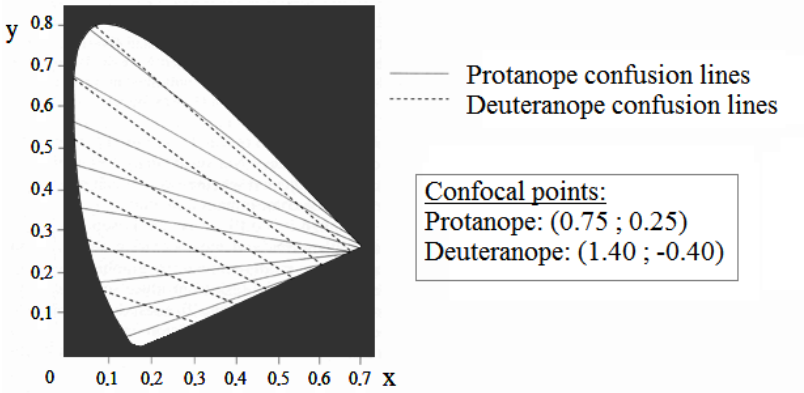

Figure 1. Protanope and deuteranope confusion lines in the CIE *xy* color diagram. Corresponding confocal point coordiantes are given.

2.3. Pseidoisochromatic tests

The construction of pseudoisochromatic (PIC) plates is based on the selection of colors on the confusion lines. In addition, multiple luminance values are added for masking the influence of luminance hues on stimuli detection (Dain, 2004[b]). PIC tests are not only printed (Richmond HRR, Ishihara), but also computerized (Cambridge color test, Color Assessment and Diagnosis). In opposition, there are other construction principles in color vision test development like the Rayleigh equation (anomaloscope), relative brightness perception combined with PIC color choice (Farnsworth Munsell 100-hue) etc.

2.4. Terminology in psychophysics

Psychophysics is the study of the relationship between physical stimuli and perceptual responses. **Perception** (the appreciation of a physical situation through the mediation of one or more senses) is a process that occurs inside our brains and cannot be measured directly. It is possible to scientifically study the relations between a physical stimulus and response of the observer. The stimulus is physical entity and described by a quantitative value. (Norton *et al*., 2002)

Threshold of visual perception is the most commonly used measurement in psychophysics – it refers to a boundary separating stimulus values that elicit a response from stimulus values that do not elicit a response. **Psychophysically measured threshold** values can vary due to stimulus fluctuations, neural activity, attention and psychological bias. (Norton *et al*., 2002)

On of the most precise and often used psychophysical methods is the **method of constant stimuli** – a fixed set of stimulus values are selected (5 to 9) such that the lowest values are expected to be slightly below the threshold value, and the highest values – slightly above. Each stimulus value is presented many times in random order. Each trial the participant is asked (in the most simple cases "yes"/"no" answers are requested) to indicate whether the stimulus was detected. For the calculation of the threshold value a "S"-shaped (psychometric) curve is constructed: the percentage of times the subject detected the stimulus against the stimulus dimension. Threshold is taken as the point where stimulus was correctly detected 50% of the time (guessing rate and other biases are also taken into account). (Norton *et al*., 2002)

3. Experimental part

3.1. Color matching experiment and development of pseudoisochromatic test KAMS

KAMS (a term comprising the names of the test developers: Kaiva, Ausma, Māris, Sergejs) was created as printed psychophysical PIC test for detecting and classifying red-green color vision deficiency and severity level determination of the CVD. Unlike other color vision tests used in clinics, it characterizes the severity of deficiency in numerical units associated to sensitivity loss along the color confusion line. The outcome result of the test is an individual color discrimination threshold value described by a commonly used quantity in science – total color difference in CIE LAB color space ΔE^*_{ab} (ΔE). KAMS test result is a numerical threshold value, which gives our test additional value - scope for use in psychophysical investigations.

The KAMS test was designed using the principles described by Birch, 1993, using neutral colors (i.e., colors that are confused with gray). To put it in other words, the colors used in the creation of KAMS are in close proximity or along the respective deutan and protans confusion lines intersecting at the achromatic area in the CIE *xy* color diagram.

3.1.1. Acquisition of color pairs and their chromatic values for creation of test

KAMS color vision test differs from other tests by another quality – the selection of colors is based on matching experimental data performed by protan and deutan color deficient individuals of various extents of the deficiency. In other color vision tests the stimuli/background color and luminance value relationships are chosen based on the changes in relative brightness perception.

In total, more than 300 chromatic and 106 grey color samples along and next to the deutan and protan color confusion lines passing through the achromatic area in the CIE *xy* color diagram were created. Samples had various saturation and lightness levels, and were 3 x 3 cm.

Five CVD individuals (3 deutan, 2 protan) performed matching experiments under controlled illumination conditions (using a Qualitest CT-100W1 light booth under D65 illumination with a color temperature of T = 6500 K).

The subjects were given two tasks: first, to sort samples into stacks of gray and chromatic, and second, to sort gray samples in piles of similar lightness (before the experiment the subjects and author agreed on the mutual understanding of term “gray” (absence of hue and chroma characteristics)). In a similar manner, via two subsequent trials, subjects matched more samples,

which we created, to achieve a gradual increase in ΔE in the KAMS test plates for both protans and deutans, along both directions from the achromatic point. Henceforward the expression "**color pair**" stands for the chromatic values of two samples – colorful (hued) and achromatic that were indistinguishable in case of a specific CVD (see Figure 2). The printing method, its advantages and disadvantages are described below.

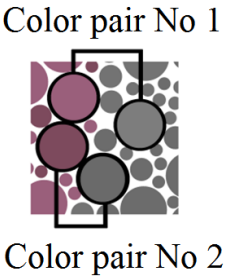

Figure 2. Both color pairs (lighter pair (No. 1) and darker pair (No. 2)) are shown. Two color pairs formed one PIC plate.

3.1.2. Creation of test plates and patterns

KAMS test first version (which was used for test performance assessment and first attempt of color discrimination threshold calculations) was a set of 24 PIC plates (10 for protan deficiency (5 reddish and 5 greenish) and 14 for deutan deficiency (9 reddish and 5 greenish)). It was created based on psychophysical design. Each plate had two patterns - circle sets (A) and (B), where only one held a chromatic symbol. The symbols used were four different digits with a rounded shape (i.e., 6, 8, 9, and 0), giving a guessing rate for each plate of 12.5%. Figure 3 shows an example of a plate for detecting deutan deficiency (the corresponding ΔE for the printed plate is 27 units). The observers had two tasks: detection (to determine whether pattern (A) or (B) contains a symbol) and recognition (to determine which of the four numbers the pattern contains). Each plate was printed on a single A5 page. The pages were turned at 3-s intervals.

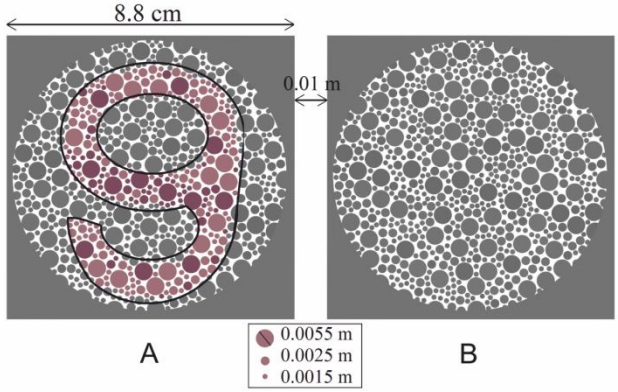

Figure 3. Each large circle set ((A) and (B)) was composed of equal numbers of small dots, with three different sizes, some of which formed the shape of a symbol. The proportion of lighter symbol-forming dots to darker symbol-forming dots was constant for all plates. Circle (A) contains the chromatic symbol "9" (shown with a black outline for clarity in the black and white prints of the thesis summary), and circle (B) is empty. In this case, the deutan classification plate with $\Delta E = 27$ is shown.

Increasing difficulty of the plates was achieved by decreasing ΔE of the test stimuli and the background. Such an approach has been reported previously (Wenzel, Samu, 2012). The symbol on test plates was composed of two stimuli–background-forming dot pairs (one lighter and one darker). The lighter pairs (making up 57% of the body of the symbol) were chosen to closely match the intensity (and accordingly the ΔE) of the darker ones; the deviation in most cases was less than a few units. The calculation of the color pair ΔE values was performed based on data obtained using a Konica Minolta CS-100A colorimeter (CIE *xy* diagram color space coordinate *x*, *y* and Y values were recorded). Samples were illuminated with simulated D65 (T = 6500 K) illumination via a Qualitest CT-100W1 light booth. Color differences were calculated using the formula proposed by Berns, taking into account the differences in sample lightness (ΔL^*), chroma (ΔC^*_{ab}), and hue (ΔH^*_{ab}) (Berns, 2006), i.e:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2} \quad (1)$$

3.2. Printing method and stability of KAMS test colors

3.2.1. Printing method of samples and test plates

In order to carry out the author's objective - to create a PIC test that characterizes individual color resolution by a precise threshold value, the

stimuli of the test itself must be reproduced as accurately as possible - an appropriate printing method must be selected to reproduce the desired color with smallest possible chromatic value dispersion. Commercially available color vision tests are made using offset print. Offset print was not suitable for our cause firstly because colors from the same test plates but different editions have significant chromatic variations that result in clinical misevaluation. Secondly, the spread of the chromatic values using offset print would be too wide to assure that the appropriate ΔE within one plate does not differ by more than one-two units (Fomins, Ozolinsh, 2011; Lee, Honson, 2003; Dain, 2004[a]). In search of best method of print, the author mutually analyzed two printing methods – inkjet print and photographic print.

In case of **inkjet printing**, the final image is produced by applying series of ink dots for resulting appearance of color. The samples were printed using a calibrated inkjet printer (EpsonStylus Pro 7800) using nine UltraCrome K3 Epson Ink cartridges (4 types of black, light cyan, light magenta, cyan, magenta, and yellow) on Premium Semimatte photopaper 260, with a resolution of 2880 dpi.

Photographic print - a process of producing a final image on paper, using chemically sensitized paper. In photographic printing process, the tiny dots produced by chemical reaction are observable under 100 x magnification. Color samples and test plates were created using a calibrated *Noritsu HD 3701* digital printer (640 dpi resolution). Printing was done on silver-halide (AgX) color-negative *Kodak Professional ENDURA* paper (F-glossy paper type).

3.2.2. Multispectral analysis of print images

The method described below was used throughout the study (to describe the samples used in the matching experiments, in cone signal modeling, and plate color fading analysis).

Multispectral imaging was performed using a CRI Nuance Vis 07 multispectral camera with a Nikon AF-S Micro-Nikkor 60-mm *f*/2.8*D* objective lens. Image acquisition was performed in an otherwise dark room; the samples were inserted in the Qualitest CT-100W1 light booth; the samples were attached to the wall at a constant height and 50±5 cm away from the camera, and were illuminated from above using a standard D65 light source (T = 6500 K). 1290 × 920 pixel spatial images were captured at visible wavelengths (420–720 nm, in steps of 10 nm). The images were transformed into cone excitation images using cone sensitivities (the method is described in detail in (Fomins, Ozolinsh, 2011)). Selected image areas of 89 pixels were analyzed, and CIE *xy* color space (x, y, Y) values were acquired for each pixel.

The comparison between the printing methods was made by analyzing the following parameters:

1) Sample chromatic value relations to confusion lines (see section 3.3.)

2) Color coordinate dispersion analysis

Printing quality was analyzed in terms of image pixel color coordinate mean value dispersion in CIE *xy* diagram for printing method used. For mean value comparison statistics tool *independent sample t-test* was used with confidence level 95%. For dispersion description Gaussian curve standard deviation (SD) of data was calculated.

3) The overlap of pixel data sets

For the inter-plate color variability assessment, the pixel values of 3 plate areas similar in color but different in position were analyzed for overlap. In case of ink print *x* coordinate, 2 out of 3 data sets overlapped (0 in case of photographic print). In case of ink print *y* coordinate, 3 of 3 data sets overlapped (2 in case of photographic print). The probability of data sets to overlap was higher in case of ink print. See Figures 4 and 5 for inter-plate color variability analysis in case of each print type (each ellipse half-width represents pixel distribution SD and the center of the ellipse – pixel mean value, along both - *x* and *y* axis).

The SD's of 32 data sets were compared (8 colored samples for each print type (2) for each of the chromatic coordinate (*x*,*y*)). Statistically the mean photographic print color dispersion (*x*=0.0017; *y*=0.0018) was larger compared to ink print SD's (*x*=0.0016; *y*=0.0014) along both *x* and *y* axis. Thus, it was observer that the area size containing each set of data points in each case of print technology differs along the *x* and *y* direction in the CIE *xy* color diagram.

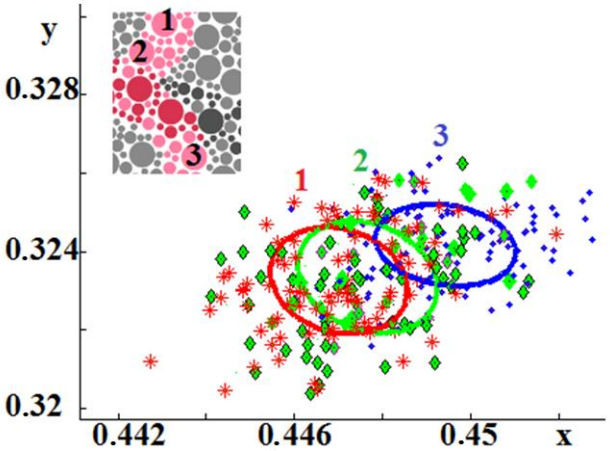

Figure 4. Pixel chromatic values (sample in inkjet print).

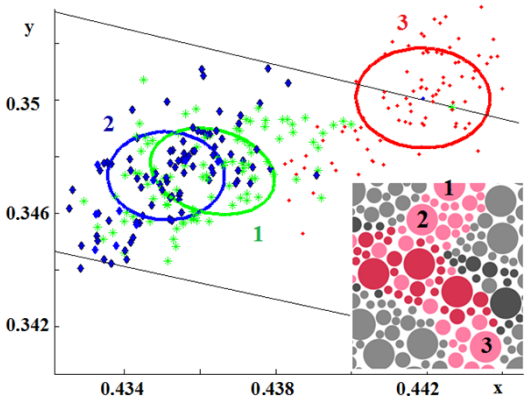

Figure 5. Pixel chromatic values (sample in photographic print).

3.2.3. Conclusions

1) In case of inkjet prints (for created plates) the mean sizes of ellipses representing pixel dispersion of each individual color array of a plate are smaller than in case of photographic prints.

2) In case of inkjet prints (for created plates) the mean distances between the centers of ellipses representing pixel dispersion of two or more equal color arrays in different spatial positions of a plate are smaller than in case of photographic prints.

3.2.4. Printing method and assessment of KAMS test fading

Hereafter all test plates were printed using inkjet print. As the result of the test is calculated depending on the given answers assuming that each test plate has a certain background/stimulus color difference relationship, all color changes due to fading are undesirable. Changes in the mean color values of the pixels and the corresponding pixel distributions (and intended ΔE of color pairs) were not statistically significant during the first three months of use (while the data were collected with each test version). Commercial distribution of the test was not planned which is why color changes and fading in prolonged periods of time are not considered shortcomings of the test.

3.2.5. Mutual shift of ellipse (representing pixel data set) centers as a result of fading

Using calibrated inkjet printing instead of typography methods to produce PIC plates showed that several aspects should be considered, such as a smaller spread of chromatic values (Luse *et al.*, 2012); however, the main drawback is faster changes in color over time (Lee, Honson, 2003; Lee, 2006).

The author has reported significant changes in the plate stimuli color saturation after seven months of use (Luse *et al.*, 2013). Prior to and throughout the study, the fading of pigments was monitored monthly using multispectral imaging, and the colorimetric measurements described above. Changes in the mean color values of the pixels and the corresponding pixel distributions were not statistically significant during the first three months of use, as shown in Figure 6.

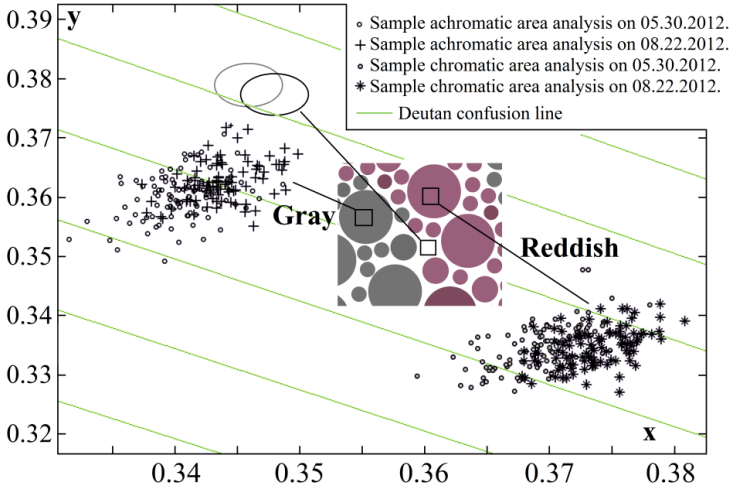

Figure 6. Pseudoisochromatic (PIC) plate image pixel color dispersion changes over 3 months in the CIE *xy* color space (one plate stimulus is shown). Statistically significant fading was not detected (data points in both sets for both color pairs – chromatic and achromatic – overlapped and were of equal size). The ellipses show an analysis of the yellowing of the white paper (black to gray). The paper color coordinate values were more consistent than those of the printed areas, therefore the ellipses (and data point distributions that are not shown in the graph) were smaller than the other pixel value distributions.

3.3. Sample color and confusion line placement relations

Over the course of several color matching experiment trials, 60 valid color pairs (a reddish or greenish sample for stimuli and a corresponding gray sample for background) were obtained for construction of PIC plates. A color pair stands for one valid greenish or reddish sample and its corresponding achromatic pair for stimuli/background formation. The colored dots on each plate had chromaticity coordinates that lie on or close to the protan or deutan confusion line connecting the dichromatic confusion line copunctal point and

each chromaticity coordinate "cloud" center of the gray background color (see Figure 7 for details).

The confocal points used are given by CIE chromaticity coordinates (0.75, 0.25) for protan and (1.40, -0.40) for deutan deficiencies (Birch, 1993). All obtained chromatic sample relations (that is, the distances *d*) to confusion lines were analyzed to answer the following question: *how far from the corresponding theoretical confusion line (for the congenital color-vision-deficient individual) may the colored stimuli chromaticity coordinate distribution center be situated and still prove to be indistinguishable from its achromatic pair*? For these calculations, equations describing coordinate geometry were used. If a line is given by two points (x_1, y_1) (i.e, the deutan or protan confusion line copunctal point) and (x_2, y_2) (i.e., the center of each achromatic sample pixel color coordinate distribution center), and the point in question is (x_0, y_0) (i.e., the chromatic sample color coordinate distribution center), *d* can be found as follows:

$$d = \frac{|(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)|}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \qquad (2)$$

The results for deutan and protan sample color pairs are shown in Figs. 7**(A)** and 7**(B)**, respectively. It was found that larger shifts from the confusion line are acceptable for the observers if the sample was less saturated. As the color difference increased, the acceptable shift decreased for greenish and reddish samples. It is not surprising that larger shifts in the greenish zone of the CIE *xy* color diagram can be tolerated because of the size increment of the McAdam ellipses in the green area compared with the red area.

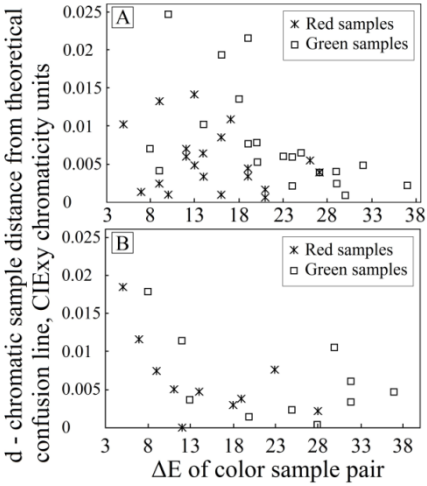

Figure 7. Graph **(A)** depicts the distance *d* for each chromatic sample from the line defined by the deutan confusion line copunctal point and the corresponding achromatic pair in the CIE *xy* color space (on the *y*-axis) for deutan samples as the sample color difference increases in CIE LAB color space (on the *x*-axis). Graph **(B)** depicts the corresponding distance *d* for protan plate analysis.

Author proposes that the tolerated sample shifts for red–green CVD individuals in the color diagram form the pattern shown in Figure 8. This hypothesis requires further investigation. Matching experiments for stimuli with a larger color difference might have been unsuccessful (even for deuteranope and protanope observers) because the color coordinate distribution of the printed areas exceeded the acceptable shifts in the saturated areas in the color diagram (see Figure 8). To paraphrase, even though participants of the matching experiments were offered a large number of samples with high saturation levels (with a precise alignment with protan and deutan confusion lines), participants sorted the samples as „hued/colorful". At this point the author cannot propose a valid explanation.

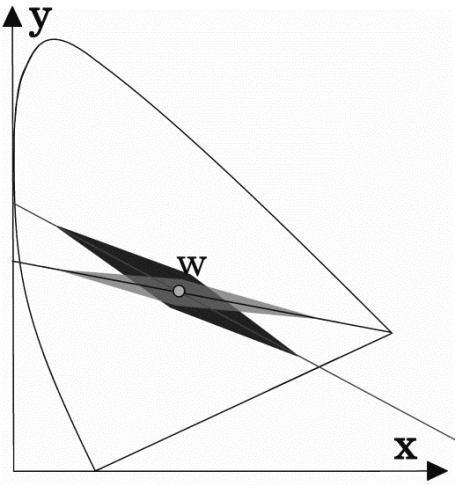

Figure 8. A possible explanation for the results shown in Figure 7. The acceptable shift (darker area) from the deutan confusion line decreases as the stimuli intensity increases. The acceptable shift distance for protans is shown as the lightest shaded area. The area suitable for screening purposes (i.e., the overlap area) is highlighted in gray. (These areas are not shown to scale.)

3.3.1. The measurement of isochromatic areas in altered color vision

We have developed a tool for detecting individual isochromatic areas in color space among color vision deficient patients. Our modified derivative of the CAD (Color Assessment and Diagnosis) test allows to quantitatively measure the degree of vision function loss associated with color perception. The colored stimuli are chosen on mutually parallel lines in the CIE *xy* color space CRT gamut. Isochromatic areas for particular person with known color vision deficit are determined by comparing the results within and among the predefined lines. Using the psychophysical design of the test we were able to

determine individual confusion lines. Results from two deutan observers show that our method is valid for finding isochromatic areas within color deficient patients in the CIE *xy* color diagram. Very high correlation with deutan isochromatic lines was obtained. Novelty of our method is the ability to acquire isochromatic area dimensions in opposite direction - above and below the corresponding confusion lines. Furthermore we aim to improve overall testing method and gather data from larger and more diverse sample size.

3.4. Assessment of KAMS test performance

3.4.1. Cone signal modelling for various characteristics of deficiency

Multispectral imagery provides an opportunity to assess the performance of the developed test using cone response mathematical modeling. In order to obtain M-cone and L-cone response simulation for protan and deutan defect types, the obtained spectral images were converted to cone responses using cone sensitivity functions (method described in detail (Fomins and Ozolinsh 2011)). Figure 9 shows the resultant opponent red-green channel response to a plate intended for deutan deficiency detection (stimulus/background ΔE = 27 units). The dotted line indicates the proposed resolution limit.

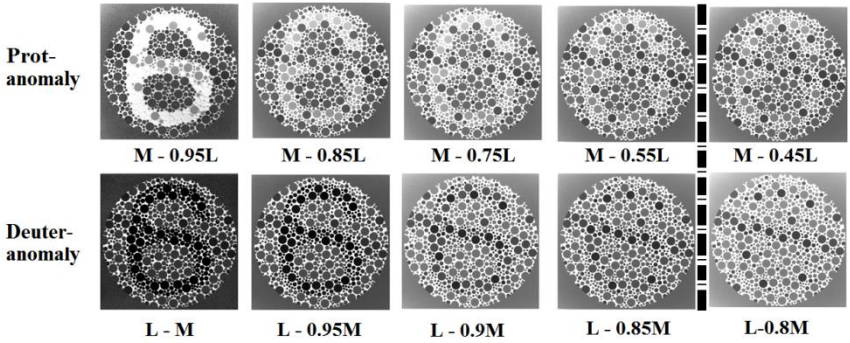

Figure 9. Simulated red-green opponent channel response (plate intended for deutan deficiency detection (corresponding stimuli/background ΔE = 27 units). Simulation shows that relatively smaller M-tcone response function reduction causes loss of stimuli information in the opponent channel response.

3.4.2. Verification of KAMS test in population study and group of participants with previously diagnosed red-green color vision deficiency

3.4.2.1. Participants

Children in two Latvian schools were tested to assess the clinical validity of the KAMS test. In total, 273 children (136 girls and 137 boys) from the Vainode region (Vainode secondary school) and the Priekule region (Gramzda elementary school) in Latvia participated. These two schools in the periphery of our country were chosen to represent our population for a number of reasons: first, to join these schools, there are no specific requirements in terms of IQ, gender, or future choice of profession, which might lead to the sample being unrepresentative; second, school children form a group of individuals that is relatively homogeneous in age. The participation rate from both schools was 84.5%, and the age range was 7–19 years (with a mean age of 12.1 and a standard deviation of 3.3 years). The study was conducted from mid-September to mid-October, 2012. Additionally, 57 volunteer individuals (with an age range of 7–67 years) with red–green CVD's were examined from mid-September to mid-December, 2012. The study was conducted in accordance with the principles embodied in the Declaration of Helsinki Code of Ethics of the World Medical Association. All participants were unaware of the specific aims of the study.

3.4.2.2. Experimental procedure

The room was illuminated using Narva LT-T8 18-W Colourlux plus CW (cool white) light bulbs. The color-rendering index of the bulbs was > 80, the correlated color temperature was T = 4000 K, and the mean illumination of the test plates was 400 lx. It has been shown that fluorescent light sources are acceptable for color-vision testing (Dain *et al*., 1993).

The visual acuity of the children was examined using a LogMAR chart with the Landolt ring optotypes. If the near visual acuity was sufficient (better than 0.2 LogMAR), each child was tested using the fourth edition of the Richmond HRR plates (Richmond Products, Albuquerque, NM), which is recommended for clinical use due to the high diagnostic accuracy (Cole *et al*., 2006; Cole, 2007; Dain, 2006), as well as the KAMS test. HRR uses neutral colors (similarly to KAMS). It was expected to acquire comparable diagnostic and deficiency type classifying performance with HRR and KAMS tests, and at least moderate result correlation due to similarities in the construction of both tests. In the event that a single error was made in any of the above tests, an Oculus HMC (R) anomaloscope (type 47720) was used, and the Farnsworth D15 saturated and desaturated (Cole, Orenstein, 2003) testing procedure was carried out. Children were classified as color-vision-deficient only if they failed the anomaloscope test.

The HRR and KAMS tests were also carried out on the volunteer participants. If the anomaloscope and/or the D15 testing procedures were available, they were also performed. All of the volunteers undertook at least three of the above-mentioned tests. In total, results from 65 CVD individuals (8 schoolchildren and 57 volunteers) were recorded; 21 subjects were classified as protans and 43 were classified as deutans (forming a large enough group of color-affected individuals for hypothesis testing, compared to other studies in the field (Huna-Baron *et al*., 2013; Lillo, *et al*. 2014)). It was not possible to interpret the results obtained with a single observer; hence, these results were excluded from further analysis.

3.4.2.3. Results: sensitivity and specificity of KAMS

The ability of the KAMS test to diagnose red–green CVD was calculated based on data acquired in the population study (schools in Vainode and Gramzda). With the chosen criterion (> 1 error), the sensitivity of the test was 100%, and the specificity was 99.62%. The sensitivity was defined as the percentage of people with the condition that tested positive, and the specificity was defined as the percentage of people without the condition that tested negative (Norton *et al*., 2002).

3.4.2.4. The ability of KAMS to classify the type and severity of red-green color vision deficiency

Although the PIC plate results alone should not be used to diagnose type of color-vision deficiency, we performed such an analysis to determine the suitability of the test for color discrimination threshold determination for protans and deutans using separate plate groups. First, each individual participant was diagnosed as protan or deutan using the test battery described earlier.

From the 64 individuals, in total, the HRR test misdiagnosed 1 deutan and 2 protans, and in seven cases, the HRR test failed to classify subjects (that is, it showed an equal number of errors in deficiency type specific (protan and deutan) column). KAMS test misdiagnosed 5 deutans and 1 protan, and in two cases classification failed. We compared the ability of the KAMS test to grade the severity of the deficiency with that of the HRR test. Moderately good agreement was achieved ($r = 0.74$ and $p < 0.01$) in the case of protans. Test results for deutans are shown in detail in Figure 10.

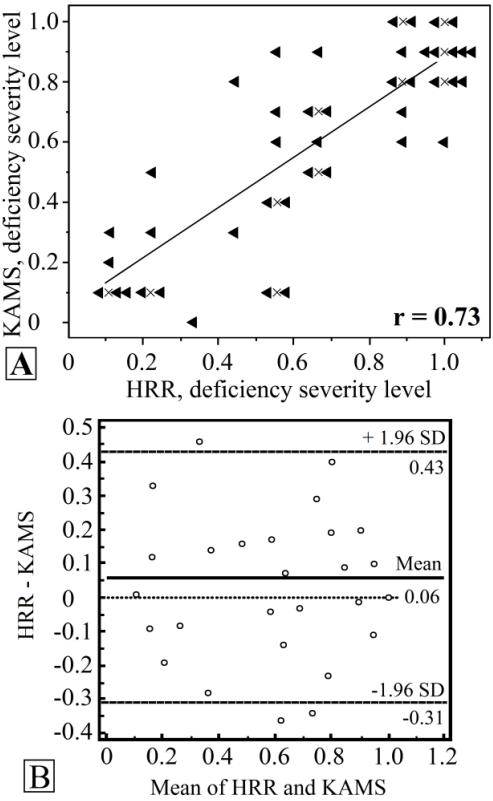

Figure 10. Comparison of the Hardy–Rand–Rittler (HRR) and KAMS test results in terms of grading the severity of the deutan deficiency (n = 43). The results of the screening plates are omitted. Graph **(A)** shows the number of errors made in the specific deutan grading plates with each test. A result of 1.0 corresponds to mistakes in all specific deutan plates, whereas a result of 0.5 means that 50% of the grading plates were determined correctly. The results of the two tests show a moderately high correlation (r = 0.73 and $p < 0.001$). A linear trend inferred from the data is also shown. Data points that overlap were offset from their true locations for demonstration purposes. The actual positions of the overlapping points are marked by the crosses. Graph **(B)** shows the Bland–Altman plot for both methods (using the MedCalc software package). No consistent bias was detected, and the difference in the sample means was not statistically significant (p = 0.05).

3.4.3. Color discrimination threshold acquired with KAMS1 test

Following the diagnosis of each participant as deutan or protan, his or her results from the KAMS test were analyzed to determine the potential of the

test for the evaluation of color discrimination threshold in ΔE units for reddish and greenish plates separately. If, for example, the subject's answers to the plates with ΔE values of 9, 10, 12, 17, 19, 21 and 27 were, respectively, wrong, wrong, wrong, wrong, correct, correct and correct, then the color discrimination threshold would be recorded as between 17 and 19 units (with a midpoint of 18 units and an uncertainty interval of ± 1 unit).

If all plates were answered incorrectly, it was assumed that the color discrimination threshold was between 27 and 60 units. At least two correct consecutive answers were required to assume that the threshold was between 0 and 27 units.

3.4.4. Color discrimination threshold in case of mild color vision deficiency and it's correlation with RGI

A convenient unit for characterizing red–green discrimination sensitivity is the red–green discrimination index (RGI), which is defined (Barbur et al., 2008) as:

$$RGI = \left[1 - \frac{(R - MR)}{73}\right] \quad (3)$$

In 3 *R* is the test subject's Nagel matching range, and *MR* is the mean normal subject's matching range. This definition results in RGI values that range from zero (in the case of dichromacy) to about one (in the case of high red–green color discrimination) (Barbur *et al*., 2008). RGI result 1 does not necessarily mean that color vision is unaffected, in corresponds to a narrow matching range.

As expected, there was a moderately strong negative correlation between the midpoint threshold values obtained using the KAMS test in deutan (n = 22) observers (r = -0.46 and p = 0.042 for thresholds obtained with reddish plates, and r = -0.44 and p = 0.042 for thresholds obtained using greenish plates). The relationship is shown in Figure 11 in the case of deutan observers for thresholds obtained by reddish plates. Identical (positive only) correlation coefficients and *p*-values were obtained for the correlation of the anomaloscope matching range to the obtained threshold values. Because of the small number of protan observers (n = 13), a negligible correlation was obtained for threshold values obtained using the green test plates (r = -0.09 and p = 0.775), and a moderate negative correlation was obtained for threshold values from the reddish test plate results (r = -0.33 and p = 0.263).

Figure 11 shows individual color discrimination threshold midpoints; two data distributions can be distinguished separated by an empty area in the center of the plot. In reality, it was possible to obtain a valid threshold region with limits from both sides only for the participants corresponding to data

points on the left-hand side of this graph. For the participants marked by points on the right-hand side, it was possible (with the PIC plates available) to be certain only about the smallest threshold midpoint region. To tackle this problem, a ΔE value of 60 units was used as the largest possible threshold value in the case of each participant for the data clustered on the right-hand side of the graph. The midpoint was calculated keeping in mind that there is a large position uncertainty in the precise thresholds of the midpoints. In other words, those subjects with lower color discrimination thresholds had a higher red–green discrimination index; however, subjects with higher color discrimination thresholds than we could determine may have various RGIs. Author can only suggest that, based on the distribution of data points on the left-hand side of the figure, these other data points might be aligned along a line with a negative gradient (shown in Figure 11), if the testing method were improved. Nonetheless, it has been shown that a lower color discrimination threshold in ΔE units is consistent with smaller matching ranges in the anomaloscope testing procedure for deuteranomalous observers.

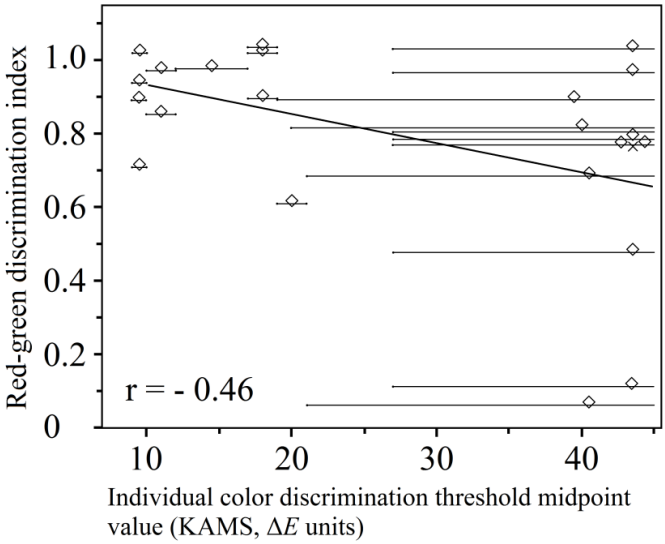

Figure 11. Individual color discrimination threshold's midpoints obtained using the KAMS test as a function of the red–green discrimination index (deutan subjects, n = 22; 3 deuteranopes, 19 deuteranomalous). Overlapping data points are offset from their true location (actual positions are marked by crosses). A linear regression to the data is also shown. Lighter gray horizontal lines show the uncertainties in the thresholds.

Color vision is known to change with age (Roy et al., 1991 Paramei and Oakley, 2014). The group of individuals with affected color vision that was studied was not coherent in terms of age. A separate data analysis was carried out to eliminate the possible effects of age on the variation of the acquired KAMS color discrimination thresholds (r = 0.19) (as well as the anomaloscope matching range midpoint values (r = 0.18)). A weak correlation was found, ruling out direct causation of threshold variance due to age differences.

The results show a correlation of the individual color discrimination thresholds and the RGI for deuteranomalous individuals. Such an outcome was expected, as Cole *et al*., 2007 reported similar results for HRR grading and the Nagel matching range (r = 0.58). However, the Nagel matching range is not correlated with the obtained red–green thresholds in the Color Assessment and Diagnosis test, which uses neutral colors for the background, similar to the HRR and KAMS test (Barbur *et al*., 2008). These results might be explained by differences in the perception of rapidly moving and changing images compared with that of static images. However, the following question remains: why are the results of the Farnsworth D15 test not comparable to the anomaloscope data (Birch, 2008)? A different approach to the analysis of the experimental data might provide other results. Furthermore, our results might be partly affected by the effect of normal age-related changes in color vision. A larger and more age-coherent sample size for the color-vision impaired group (especially in case of the protan observers) would be necessary to make a full assessment of the effects analyzed in this study.

3.4.5. Conclusions

1. The KAMS test was found to be valid for the screening of congenital red–green color-vision deficiencies, and the sensitivity and specificity are comparable to those of the HRR test (2002, 4th edition).

2. The design of psychophysical tests can be used to assess red–green color-vision deficiencies and obtain individual color saturation discrimination thresholds in the case of anomalous trichromates.

3. The size of the anomaloscope-matching range in Nagel units for deutan observers exhibited a moderately strong positive correlation (a moderately strong negative correlation, in the case of RGI) with the acquired ΔE threshold midpoints of the psychophysical testing procedure used in this study.

3.5. Repeatability of color discrimination threshold measurements

Next testing method was improved (ΔE increment standardization if possible, fined grading and transforming plate structure for psychophysical testing procedure purposes). These changes were made in order to obtain more reliable results (reduce the uncertainty areas of the color discrimination thresholds in Figure 11). Author does realize that previously described results can be questioned from the use of term "color discrimination threshold". In the research described next a new set of test plates were used – the structure transformed for psychophysical testing needs. Objectives of the sequent study were as follows: clarify whether deuteranomalous observer individual color discrimination thresholds in ΔE units are constant or variable, to describe the degree of variability, and analyze the threshold value differences with reddish and greenish plate sets separately.

3.5.1. Participants

For this stage of the study only participants with mild congenital red-green CVD were selected. They were not informed of specific aims of the study and had no previous experience with psychophysical testing procedure or knowledge on color vision testing principles. 4 male subjects participated in the study (10 – 24 years old). They all were diagnosed as deuteranomalous using HMC anomaloscope and Richmond HRR test plates. The color vision deficiency of the participants is analyzed in detail in table 1.

Table 1. Participants of the study and their results in color vision tests (*Oculus HMC* anomaloscope and *Richmond HRR*). NS – name, surname; MRM - matching range midpoint; AQ – anomaly quotient.

No	**NS**	***(MRM)***	***(AQ)***	**Err. count (HRR)**	**Result (*HRR*)**	**Result (Oculus HMC)**
1.	KS	32.0	20.7	4	Mild red-green deficiency	Deuter-anomaly
2.	EV	26.0	6.2	3		
3.	RV	24.0	19.8	3		
4.	FR	20.7	6.4	2		

3.5.2. KAMS2 test setup

The test was composed of 26 plates, 21 were specific (intended for protan or deutan deficiency), the remaining 5 plates were intended for both red-green color vision deficiency types. The plates had similar design as KAMS1 –

each pattern pair ((A) and (B)) held only one stimuli. Test plate stimuli were one of the following numbers “0”, “6”, “8” or “9”. The main difference from the previous test version was the number of pattern pairs in each plate with intended stimuli/background color difference – each plate held six pairs of pattern pairs (A) and (B) (see Figure 12). The type and placement of the colored stimuli in the plates were randomly selected.

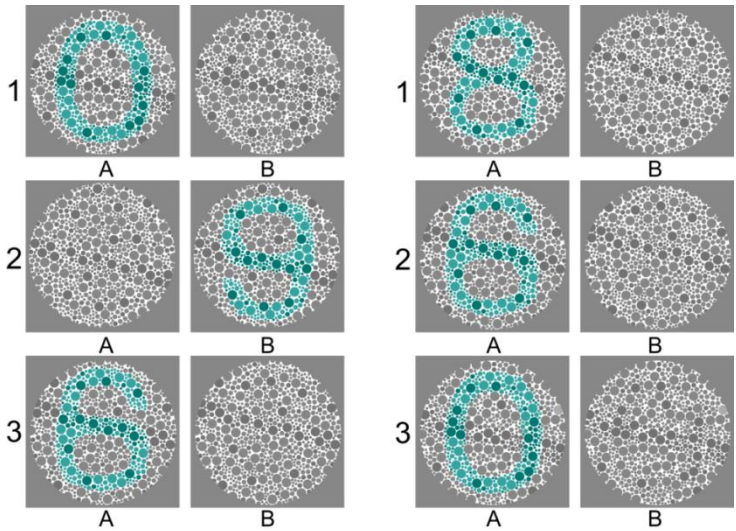

Figure 12. Plate example of KAMS test version 2 (KAMS2). Corresponding ΔE = 24 units, plate intended for protan deficiency type detection. All six pairs of images were printed on a single A4 page.

3.5.3. Experimental procedure

Participants had normal or corrected to normal near vision. The observer was sitting by a well illuminated table surface (400 lx) (a desk lamp was used with a tungsten light bulb, corresponding color temperature T = 2789 K). The conditions were held constant during all five trials. The data were collected from December 2013 to January 2014. KAMS2 test plates were printed a week before the experiment for best color reproduction.

The test was held at 0.40 m distance. Test plates were turned at 3 x 6 s intervals (3 seconds were given for the answer to each pattern pair). The participants were not allowed to move or change viewing conditions or otherwise interfere with testing procedure.

Participants had to answer the following question*: “which pattern holds a number – (A) or (B)”*? The participant had to take a forced choice regardless whether he saw or missed the stimuli. Each subject participated in five trials (in

five different days). Constant stimuli method was used in the study. At each of the five sessions the plates were shown in random order to minimize the risk of memorizing the stimuli configurations. The guessing rate of the stimuli location was 50% (two alternative forced choice) and the discrimination threshold is calculated at 75% correct mark. Color discrimination thresholds were calculated for greenish and reddish plate groups separately for all five different trials. The calculation of the threshold values were performed using *OriginPro 8.0*. Sigmoidal psychometric function was used for assessing individual color discrimination thresholds in ΔE units.

3.5.4. Results

Analysis of color discrimination thresholds in several subsequent measurements did not reveal convincing proof of threshold value variability over time (see table 2). None of the four participants showed influence of learning on the threshold value (the only exception might be participant RV – his threshold value at the first trial was significantly higher than at other four trials. In author's opinion such results can be explained from the perspective of comprehension of the psychophysical procedure not improvement of the color discrimination ability). The SD's of the threshold values might have a tendency to decrease as the discrimination threshold value decreases. The conditions of the measurement were held constant during all trials, therefore the variability of the obtained threshold values could be affected by participant neural factors and test setup. In most cases the deviation of the color discrimination threshold varied in the range of less than 2 ΔE units.

Table 2. Participant color discrimination thresholds obtained by KAMS2 test in five different trials, average threshold value and corresponding SD. Participant's KS thresholds are obtained along both sides of the neutral point. R/G – thresholds acquired with reddish or greenish plates respectively.

	Measurement No.						
Part./ (R/G)	**1**	**2**	**3**	**4**	**5**	**Average**	**SD**
FR (R)	7.0	7.5	7.6	8.1	7.8	**7.6**	**0.4**
EV (R)	9.0	9.5	7.3	9.0	7.2	**8.4**	**1.1**
RV (R)	14.2	9.8	9.1	8.0	9.5	**10.1**	**2.4**
KS (R)	10.1	10.2	12.0	13.9	13.2	**11.9**	**1.7**
KS (G)	20.5	18.2	17.9	18.5	21.2	**19.2**	**1.5**

3.5.5. Color discrimination threshold values acquired using KAMS2 reddish and greenish plate sets

Separate assessment of the color discrimination thresholds on both sides of the neutral point (with reddish and greenish plates) was conducted. In all cases it was observed that the threshold values obtained with greenish plates are larger than those obtained with reddish plates (higher threshold value corresponds to a lower sensitivity).

It can be concluded that as expected the sensitivity for the stimuli in the green plates was lower (Shevel, 2003). The results are consistent throughout the study – the measurements have been made correctly (participants with decreased M-cone sensitivity indeed have a decreased sensitivity to the green part of the spectrum compared to the colors corresponding to long-wavelengths of the spectrum). In Figure 13 color discrimination threshold values for participant KS are analyzed in detail (thresholds acquired with greenish and reddish plate groups in two testing trials).

3.5.6. KAMS2 threshold and results in clinically used tests

At this stage of the study color discrimination threshold value dependence on AQ (Anomaly Quotient) was assessed. AQ is a variable used in anomaloscope testing procedure result differential diagnosis.

$$AQ = \frac{\frac{(E-P)}{P}}{\frac{(E-M)}{M}} \tag{4}$$

In equation 4 *E* stands for the end value of the MR scale, *P* stands for test participant's adjusted MR end value, *M* stands for MR adapted value in case of observer with normal color vision. AQ result from 0.7 to 1.4 characterizes normal color vision; values from 1.4 to ∞ characterize deuteranomaly, and values from 0 to < 0.7 - protanomaly (Oculus HMC anomaloscope manual). Figure 14 shows that higher color discrimination thresholds were observed in cases of higher AQ. Similarly, a higher threshold value was observed when more errors were made in the Richmond HRR test. The acquired strong correlations allow raising a hypothesis that the results from the anomaloscope testing procedure might be computable as a function (5) from color discrimination threshold (and vice versa) (the hypothesis requires testing in a larger sample size and an improved test version):

$$\text{AQ} = 3{,}9 \text{ x KAMS} - 23{,}8 \tag{5}$$

Consequently, the results are consistent with the results acquired in the previous research (chapters 3.4.2.4. and 3.4.4.) and can be regarded as legitimated.

3.5.7. Conclusions

A total color discrimination threshold value in *ΔE* units exists for each mild deuteranomalous individual tested with the KAMS2 pseudoisochromatic plates, this threshold value does not change significantly in multiple measurements (threshold value variation was less than 2 Δ*E* units). Evidence of a predictable threshold value dynamics with a certain trend was not found. A strong positive correlation (r = 0.92) exists between anomaloscope AQ and deuteranomalous color discrimination thresholds acquired by KAMS2 test, and (r = 0.92) between error score in HRR test and thresholds acquired by KAMS2 test.

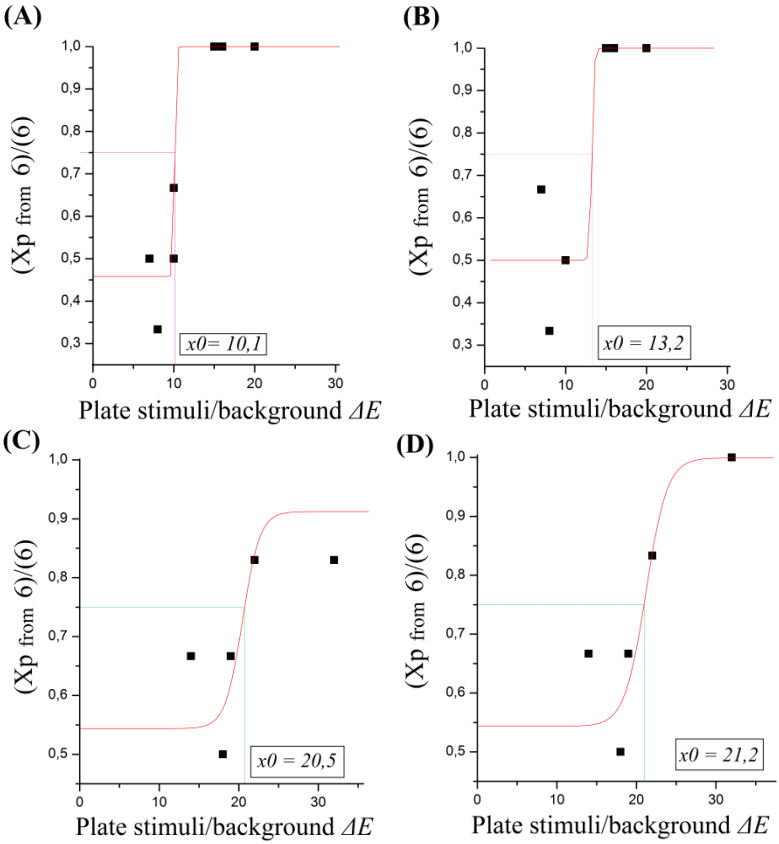

Figure 13. Color discrimination thresholds of participant KS (acquired with KAMS2). Graphs (A) and (B) show threshold values acquired with reddish plates in first and fifth (last) measurements respectively. Graphs (C) and (D) show threshold values acquired with greenish plates in first and fifth (last) measurements respectively.

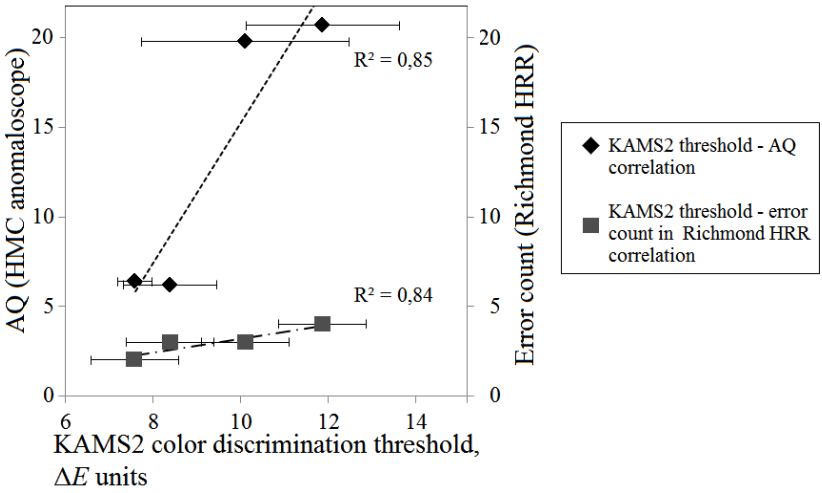

Figure 14. Correlation of color discrimination thresholds acquired with KAMS2 and (1) errors made in Richmond HRR (■; r = 0.92), and (2) AQ acquired by HMC anomaloscope testing procedure (♦; r = 0.92). Linear trend lines and SD's of KAMS2 thresholds are shown.

4. Resume

Author has compared the KAMS test with the Richmond HRR test throughout this study because the latter is one of the best clinical PIC tests (Cole *et al*., 2006; Cole, 2007; Dain, 2006). The high sensitivity and specificity of KAMS suggests that although the KAMS test was created for scientific (as opposed to clinical) purposes, it is a potential supplementary test for use in both research and clinics; author does not suggest replacing currently used tests with the KAMS test. The good level of agreement in terms of the grading results obtained using KAMS and the HRR test suggests that the tests are comparable; however, our plate set has scope for use in psychophysical investigations. The main novelty of the research is the depiction of the results of a printed PIC test via a discrimination threshold described by a numerical value. The total color difference is a commonly used quantity in science. The results given in in terms of total color difference may be useful and easy to interpret for specific applications or for product developers (the results depict color-sensitivity loss in comparison with the color-discrimination ability of a normal observer for neutral colors). Using a limited number of plates (five for greenish and nine for reddish directions in the CIE *xy* coordinates), we were able to determine individual ΔE discrimination thresholds for deutans. Souza and colleges (2014) have analyzed color discrimination thresholds with Cambridge color test. The area of color discrimination ellipses as a function of luminance steps increased for small numbers of luminance levels forming the PIC plate. The precision of the measured color discrimination thresholds would be improved if the following factors have been taken into account:

1. Greater number of each plate forming luminance levels;
2. Smaller ΔE step and a greater number of test forming plates (both – plates with new ΔE levels and already existing plate stimuli/background ΔE relations would be advisable).

Tackling the problems stated before would require significantly greater initial sample size. Printed samples are subject to fading which is why it would be more efficient to continue the research using computerized stimuli and experimental environment.

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