Multispectral analysis and cone signal modelling of pseudoisochromatic test plates

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Abstract. The aim of the study is to determine the consistency of the desired colour reproduction of the stimuli using calibrated printing technology available to anyone (Epson Stylus Pro 7800 printer was). 24 colour vision assessment plates created in the University of Latvia were analysed right after their fabrication on August 2012 and after intense use for 7 months (colour vision screening on 700 people). Multispectral imagery results indicate that the alignment of the samples after seven months of use has maintained on the CIExy confusion lines of deutan deficiency type, but the shift towards achromatic area in the diagram indicate decrease in the total colour difference (ΔE*ab) of test background (achromatic) areas and stimuli (chromatic) areas, thus affecting the testing outcome and deficiency severity level classification ability of the plates.

1. Introduction
Altered colour vision affects approximately 8% of male and 0.4% of female population and congenital red-green colour vision deficiency (M cone dysfunction - protan deficiency and L cone dysfunction - deutan deficiency) makes up most part of above mentioned percentage [1,2]. Regardless of the design used for the creation of pseudoisochromatic (PIC) tests, they are based on evoking different grouping responses in people with normal trichromatic and abnormal colour vision. Colours for such plates must be chosen in specific alignment to CIExy colour diagram confusion lines according to each deficiency type [1,3]. By careful choice of coloured symbol chromatic values and its corresponding background colour, tests characterized by high test validity can be obtained [4,5]. The amount of total colour difference ΔE*ab of the test plate determines the level of difficulty of the specific plate. The perception of colour in case of colour vision deficiencies is still studied and tests for quantitative measurement of deficiency severity are developed [6,7]. Previous studies have shown that high desired chromaticity value accuracy for PIC test creation can be obtained using calibrated inkjet printing [8]. The analysis of durability of the prints and chromatic value validity for colour vision testing purposes is the aim of this study. Previous research shows that colours from the same test plates but different editions have significant chromatic variations that result in clinical misevaluation [9].

2. Methods and experiment setup
2.1. Development of the colour vision test plates
The PIC plates were designed using the principles described in the book of J. Birch [1]. Neutral colours (colours confused with gray) were chosen for the study. The design of the experiment for acquiring...
corresponding pairs of achromatic and chromatic colour matches is described earlier [8]. A set of 24 PIC plates (10 for protan deficiency (5 reddish, 5 greenish) and 14 for deutan deficiency (9 reddish and 5 greenish)) was created (see Figure 1 for examples).

![Image of two plates]

Figure 1. Two plates of twenty four plate set are shown. A – plate for medium deutan colour vision deficiency assessment ($\Delta E^{*}_{ab} = 27$), B - plate for severe deutan colour vision deficiency assessment ($\Delta E^{*}_{ab} = 37$).

1.1. Multispectral image capture
For multispectral imaging CRI Nuance Vis 07 multispectral camera with Nikon AF Micro-Nikon 60mm f2.8D objective was used. Multispectral image capture was performed in dark room, the test plates were inserted in Qualitest CT-100W1 light booth (attached to the wall at equal height at all times, distance from the camera 55±5 cm, and illuminated from above via standard D65 light source (T=6500K)). 1290 x 920 pixel spatial images in range from 420 to 720 nm (step 10 nm) were taken. Images were transformed using cone sensitivities into cone excitation images (see [10] for details). Selected image areas of 89 pixels were analysed and $CIE_{xy}$ diagram (x,y,Y) values acquired for each pixel. Image capture was performed right after the production of the plates on August 2012 and after seven months of use on March 2013. The chromaticity coordinates x,y of 3 deutan deficiency testing plates are discussed in this paper (with total colour differences 9 (reddish), 27 (reddish) and 37 (greenish) units).

3. Results and discussion of plate multispectral analysis
3.1. Fading of the pigments and sample relations to the confusion lines.
To analyse the change of the chromatic values of the plates after seven months of use, the distance between pixel sets in $CIE_{xy}$ diagram was described using ellipses (radius of the ellipse can be defined as SD of data in x and y directions). Ellipse shift differences are plotted in Figures 2 and 3. Meaningful shifts of the chromatic areas towards the achromatic area of the diagram were obtained for all lightness levels of chromatic stimuli and all three saturation levels of the plates. Picture 3 illustrates a significant shift of the coloured areas (1) and (2) toward the achromatic area (3) and (4), the correspondence to confusion lines is not altered, similar fading was observed in case of reddish symbol plate of colour difference 27 units (data not shown). The analysis from the perspective of sample relation to confusion lines was performed as follows. Five areas in each plate were analysed, each area was measured twice. Additional interplate analysis was not performed for the consistency of chromatic values was shown earlier [8]. Figure 2 shows alignment of light chromatic (1), light achromatic (2) and white paper (3) areas in the least saturated plate (dark chromatic and achromatic areas are not shown to avoid overcrowding of the data). Figure 3 shows similar condition in case of the most saturated plate. The measured pixels of the image of the plates are in good correspondence to a single deutan colour confusion line both prior and post use.

3.2. Colour coordinate dispersion analysis
For dispersion description Gaussian curve standard deviation (SD) of image pixel colour coordinate mean values was calculated. For dispersion amplitude comparison statistics tool independent sample $t$-test was used with confidence level 95%. The pixel value deviations from mean values before and
after test use was compared for each plate’s 4 areas (light chromatic, light achromatic, dark chromatic and dark achromatic) along both chromaticity coordinates (x,y). Statistically in 11 out of 12 cases the colour dispersion is significantly larger (the ellipse is wider) in x axis direction and in 9 cases (out of 12) colour dispersion was significantly larger (the ellipse is wider) in y axis direction if compared to newly printed pigment area colour dispersions along both axis in CIExy diagram. The sizes of the ellipses have changed from (x=0.002, y=0.0026) to (x=0.0032, y=0.0036) in case of light samples and from (x=0.0028, y=0.0030) to (x=0.0038, y=0.0044) in case of dark samples.

Figure 2. Multispectral analysis of deutan deficiency plate of least saturation ($\Delta E_{ab}^* = 9$) before (x) and after (o) seven months of use. Pixel values are shown and areas marked with ellipses which centres represent mean pixel data set values and each ellipse size indicates SD’s for each pixel set.

Figure 3. Multispectral analysis of deutan deficiency plate of most saturation ($\Delta E_{ab}^* = 37$) before (dotted line) and after (continuous line) seven months of use.

3.3. Cone signal modelling
Multispectral data provide a possibility to test the developed test plate’s validity by mathematical modelling. To perform M and L cone response simulation in case of protan and deutan deficiency, spectral images obtained were transformed to cone signals using cone sensitivity functions (method in detail described in [10]). Figure 4 shows the results in case of plate designed for deutan deficiency testing (total colour difference is 27 units). Orange line line notes the resolution limit.
Figure 4. Cone signal modelling for both red-green deficiency types and various deficiency severity levels (indicated by the decrease of the multiplier value). Simulation shows that the plate is indeed more suitable for deutan deficiency testing as the symbol vanishes with smaller decrease in M cone response.

Conclusions
Multispectral analysis has shown significant fading of the chromatic colour test plate areas after seven months of use. Fading has affected plates of both saturations and both directions across CIE\textsubscript{xy} chromaticity diagram (reddish and greenish plate types respectively). The alignment of the samples after seven months of use has maintained on good correspondence to the confusion line of deutan deficiency type, but the shift towards achromatic area in the diagram indicate significant changes in the total colour difference (\(\Delta E^*\)) of background samples and stimuli samples thus affecting the testing outcome and deficiency severity level classification ability of the plates. The dispersion of the plate chromatic and achromatic stimuli along CIE\textsubscript{xy} x and y axis was larger after seven months of use.

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