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Simulating Colour Vision Deficiency from a Spectral Image

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Abstract. People with colour vision deficiency (CVD) have difficulty seeing full colour contrast and can miss some of the features in a scene. As a part of universal design, researcher have been working on how to modify and enhance the colour of images in order to make them see the scene with good contrast. For this, it is important to know how the original colour image is seen by different individuals with CVD. This paper proposes a methodology to simulate accurate colour deficient images from a spectral image using cone sensitivity of different cases of deficiency. As the method enables generation of accurate colour deficient image, the methodology is believed to help better understand the limitations of colour vision deficiency and that in turn leads to the design and development of more effective imaging technologies for better and wider accessibility in the context of universal design.

Keywords. Colour vision deficiency (CVD), CVD model, simulation, multispectral, cone sensitivity

1. Introduction

People with normal colour vision have three types of cones (L-Red, M-Green, and S-Blue) which enable us to see the world in full contrast colour. However, there are people with colour vision deficiency (CVD) who cannot enjoy full colour world because of the lack of or anomaly (defect) in one or two cone types in their vision system. There are several types of colour deficiencies based on which cone is affected and to what degree.

Colour vision deficiency can be broadly categorized into three types: anomalous trichromat, dichromat, and monochromat. People with one cone whose absorption spectrum is shifted with respect to the spectrum of a normal viewer is called *anomalous trichromats* and depending on whether the red, green, or blue cone is affected (weak), the condition is called *protanomaly*, *deuteranomaly*, and *tritanomaly* respectively. People whose one cone does not function because of the absence of or reduced sensitivity are called *dichromats* and based on whether red, green, or blue cones are affected; they are respectively called *protanopes*, *deuteranopes*, and *tritanopes*. Individuals suffering from protanopia cannot perceive any red light, those with deuteranopa cannot perceive green light, and those with tritanopia cannot perceive blue light. There are people with both red-green colour deficiency (both protanope and deuteranope). Those with

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blue-yellow deficiency, which is rare falls within the tritan case. People with two or three non-functioning cones are called *monochromats*, and they are completely colourblind, i.e. they cannot see colour at all. There are 7-10% of males who have some form of red-green colour deficiency, 2.4% males and 0.03% females have some form of dichromacy, and 6.3% of males and 0.37% of females have some form of anomalous trichromacy [1, 2]. Different techniques are used to diagnose colour deficiency and anomaly such as Ishihara tests, colour arrangement tests (Fransword D-15, D-100), anomaloscopes, and pseudoisochromatic plates [3].

Since people with CVD have difficulty seeing images in full contrast, they can miss some of the features in a scene or photograph. Millions of people worldwide is affected by some form of colour vision deficiency, and so far, there is no clinical or surgical treatment available. In light of the universal design, it is important to understand the limitation of colour vision deficiency and provide solutions for better accessibility through new tools and technologies to improve the quality of life of affected individuals. Daltonization technique is used to recolour (modify the colour of) the photograph so that those missing contrast and features are made more evident. Several daltonization algorithms have been proposed with the aim of increasing the colour contrast and improving accessibility of the images in terms of retrieving information content for colour deficient people [4–8].

Daltonization algorithms use simulated colour deficient images generated based on colour vision deficiency models [9, 10]. These models are mainly based on trichromatic colour image, which has several limitations such as environment dependency, suffers from metamerism, and limited to visual spectrum. In this paper, a colour deficient image generation methodology based on a spectral image is proposed. Since spectral image mitigates the limitations of trichromatic colour image leading to accurate colour image, this enables simulation of accurate colour vision deficiency. With the availability of fast, simple, and inexpensive multispectral imaging technologies [11], the proposed method provides a feasible solution.

In the next section, we present a widely used colour vision model. Then, we briefly introduce some of the traditional model-based techniques of simulation of colour vision deficiency. Next, we present the proposed simulation methodology using a multispectral image. We discuss and finally conclude the paper.

2. Colour vision model

Colour vision is modeled by a linear system defined by the spectral sensitivities of the cones. Let $e(\lambda)$ be the spectral radiance of light (also referred to as *colour stimuli*) incident on the retina, where λ denotes the wavelength, the responses of the three cones can be modeled as a three component vector $\mathbf{c} = [c_{\mathrm{L}}, c_{\mathrm{M}}, c_{\mathrm{S}}]^{\mathrm{T}}$ given by the following equation.

$$c_k = \int_{\lambda_{\min}}^{\lambda_{\max}} e(\lambda) s_k(\lambda) d\lambda, \quad k = \{\mathrm{L, M, S}\}, \tag{1}$$

where s_k denotes the spectral sensitivity of the three cones. λ_{min} to λ_{max} is the interval of wavelengths of the visible spectrum. The spectral sensitivities outside this wavelength range are assumed zero. For non-luminous, reflective objects, the spectral radiance $e(\lambda)$ of the light incident on the retina is the product of the spectral reflectance $r(\lambda)$ of the object surface and the spectral radiance $l(\lambda)$ of the viewing illuminant. We may write Equation 1 as follows:

$$c_k = \int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} s_k(\lambda) l(\lambda) r(\lambda) d\lambda, \quad k = \{\mathrm{L, M, S}\}. \tag{2}$$

Digital colour imaging model replaces Equation 2 by their sampled counterparts to obtain summations as numerical approximations to the integrals, and it is expressed in a matrix equation form as:

$$\mathbf{c} = \mathbf{S}^{\mathrm{T}} \mathbf{L} \mathbf{r}, \tag{3}$$

where $\mathbf{S} = [\mathbf{s}_{\mathrm{R}}, \mathbf{s}_{\mathrm{G}}, \mathbf{s}_{\mathrm{B}}]$ is the matrix of camera sensitivities, $\mathbf{s}_k = [s_k(\lambda_1), s_k(\lambda_2), ..., s_k(\lambda_K)]^{\mathrm{T}}, \ k = \{\mathrm{R, G, B}\}$. $\mathbf{L}$ is the diagonal illuminant matrix whose diagonal elements are the samples $l(\lambda)$, and $\mathbf{r}$ is the sampled spectral reflectance vector of the surface.

3. Model-based simulation of colour vision deficiency

Model-based simulation techniques are mainly based on the observations from unilateral dichromats (people with dichromacy in only one eye, while the other eye has normal colour vision). These observations found that both the normal and anomalous eyes perceive achromatic colours similarly [12, 13]. An early technique by Meyer and Greenberg [14] mapped achromatic colours in approximate wavelengths of 475nm and 575nm for protanopia and deuteranopia, and 485nm and 660nm for tritanopia in XYZ colour space and drew confusion lines representing directions along which there is no colour variation according to dichromats colour perception. The simulated deficient colour is then defined by projecting the colours through the confusion lines on the reduced gamut.

Brettel et al. [9] mapped the colour gamut of dichromats onto two semi-planes in the LMS colour space, while constraining the direction of confusion lines to be parallel to the direction of the colour spaces axes L, M, or S, depending on whether the dichromacy type is protanopia, deuteranopia, or tritanopia respectively. Simulated dichromatic colour is obtained by projecting the original colour on these semi-planes. These techniques produce good results for dichromacy; however, they are not usable for anomalous trichromacy.

Yang et al. [15] proposed a simulation technique for anomalous trichromacy, based on conversion of colours from RGB colour space corresponding to a typical CRT monitor to anomalous LMS, and then converting back from LMS to RGB space. Machado [10] found that the simulated images from this technique contain colours that are not the ones perceived by individuals with colour vision deficiency. As a solution, he proposed a physiologically-based model based on two-stage opponent colour model of human colour vision, which he claimed to perform better in terms of preserving achromatic colours and simulating both anomalous trichromacy and dichromacy [16].

Most of the CVD models are based on general models hence may not reflect perceptual capabilities of an individual with CVD. Flatla and Gutwin [17] proposed an empirical model based approach for more accurate colour representation of what a particular person with CVD actually sees. However, since it is based on colour imaging model, this model is also dependent on illumination condition.

4. Simulation of colour vision deficiency using a spectral image

Spectral imaging captures images of a scene in K channels ($K > 3$) typically in the form of a spectral reflectance image of the scene. Spectral reflectance represents a unique physical property of a surface, independent of the device used to acquire and the environment under which the acquisition is made. It can also produce accurate colour image. Therefore, spectral imaging is useful in many application domains such as remote sensing, medical imaging, cultural heritage, biometrics etc. This paper explores yet another application domain, the universal design, where spectral imaging can be used in the simulation of colour vision deficiency.

From a spectral image, we can simulate a colour image under any arbitrary illumination, using a colour imaging model (Equation 3). Moreover, knowing the spectral sensitivity of the cones of an individual, we can simulate colour image one perceives under a given illumination from the spectral image, using the same model. Spectral sensitivity data of individuals can be discrepant, even if they depend on the same underlying photopigment. Measuring spectral sensitivities of cones of normal and deficient colour vision and factors that influence spectral sensitivity is described in [18].

By measuring or modeling spectral sensitivity functions for a colour vision deficiency, we can simulate corresponding colour deficient image. In this paper, results on some representative cases of anomalous trichromacy and dichromacy are presented.

Anomalous trichromacy is usually modeled by shifting the spectral sensitivity function of the anomalous cone according to the degree of severity of the anomaly. Since a shift of about 20nm of the anomalous L or M cones almost completely overlap with the normal M or L cones respectively, 20nm shift is considered a severe case of protanomaly or deuteranomaly. Similarly, we can model spectral sensitivity functions of the cones for protanopes, deuteranopes, and tritanopes with the absence of or reduced sensitivity of the red, green, and blue cones (*i.e.* red-blind, green-blind, and blue-blind) respectively from the normal colour vision. Normalized spectral sensitivity curves for these two types of anomalous trichromats, and three types of dichromats, along with the normal colour vision are given in Figure 1.

5. Simulation results

In order to illustrate the results from the proposed multispectral image based simulation, severe protanomaly and deuteranomaly with a shift of 20nm, and three extreme cases of protanopes, deuteranopes, and tritanopes where the red, green, and blue cones is completely absent respectively, and the spectral sensitivity functions shown in Figure 1 for those cases are used. First, we illustrate the simulation result for the perceived colours of the 24 patches of the standard Macbeth ColourChecker (MCC) passport. Figure 2

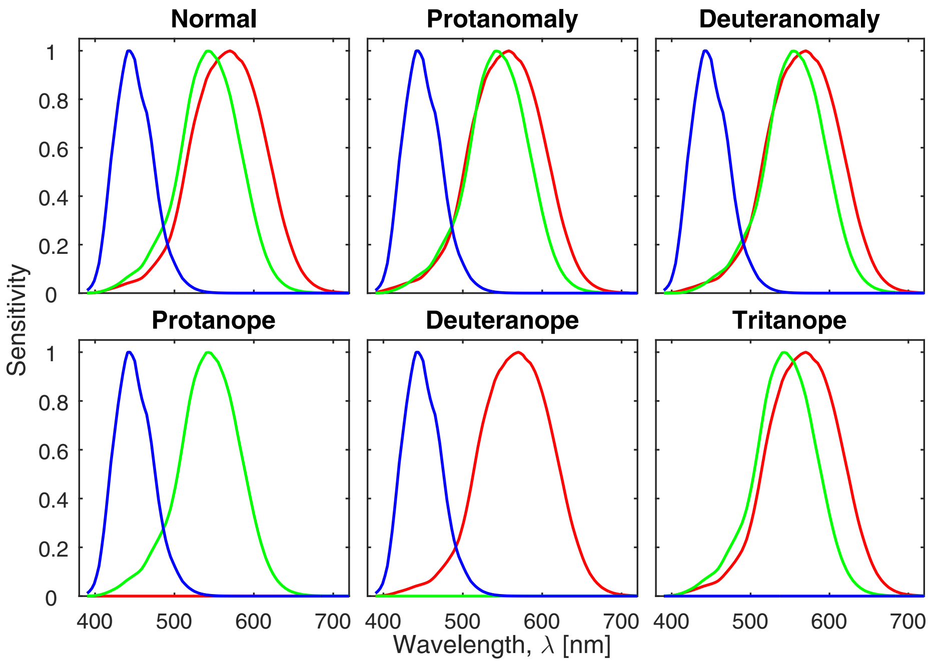

Figure 1. Normalized spectral sensitivity curves the L (red), M (green), and S (blue) cones for a normal and five colour vision deficiency cases.

shows these 24 patches along with their spectral reflectances (overlaid) as measured and used in [19]. The scene as perceived by the normal and the colour vision deficient individuals under a standard illumination CIE D65 is simulated using Equation 3. The resulting perceived colours of the 24 patches of the MCC is shown in Figure 3. The images are shown in sRGB space after the chromatic adaptation using the CIECAM02 colour appearance model [20, 21].

As two real scene examples, simulation result on a natural scene and a painting is also presented here. Figure 4 shows a natural scene as perceived in the six different cases including the normal vision. The images are simulated from the hyperspectral image available online from Foster et al. [22]. For the painting, hyperspectral image of the famous painting 'The Scream' by Edvard Munch (1893), acquired by Hardeberg et al. [23] and processed by Shrestha and Hardeberg [24] is used. Figure 5 shows the resulting perceived colour of the image as seen by the normal and the five different colour deficient people.

From the resulting simulated images, we can see how colour deficient people perceive the colours of the scenes differently. We can also see that they face difficulty distinguishing some colours, which causes them to miss some of the image features in an image.

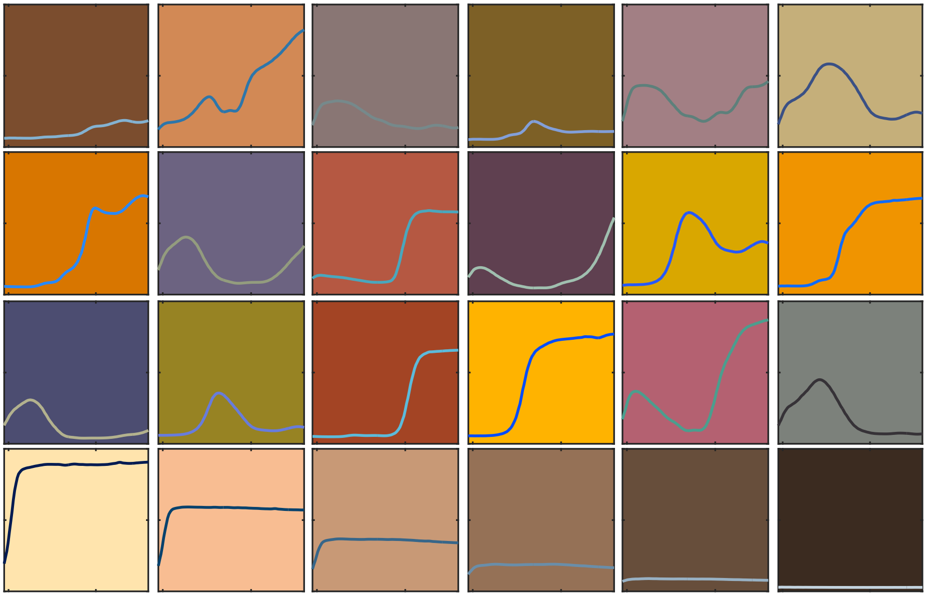

Figure 2. 24 patches of the Macbeth ColourChecker and their spectral reflectances.

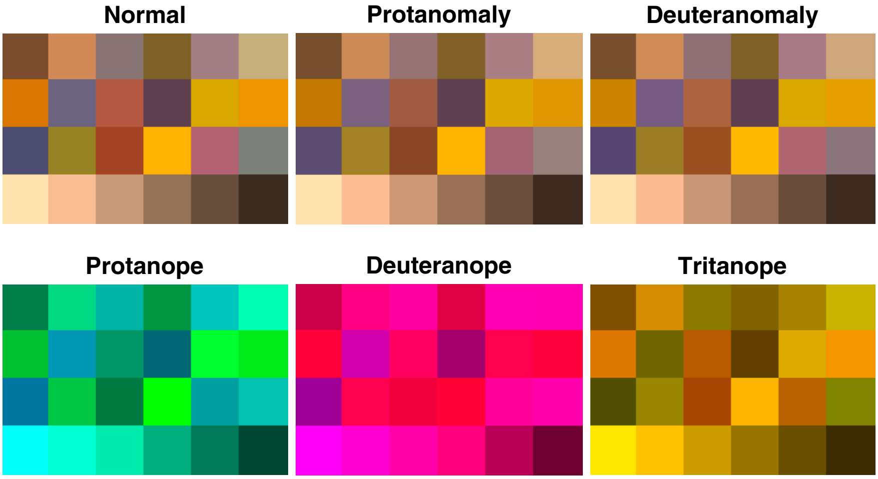

Figure 3. Simulated colour of the 24 patches of the Macbeth ColourChecker as perceived by the normal colour vision and the five different colour vision deficient people.

6. Discussion

Model based techniques use colour image, which is environment dependent and suffers from metamerism. Multispectral imaging offers environmental independent and accurate colours. Because of cost, complex calibration process and slow acquisition speed, multispectral imaging used to be limited to indoor research and high-end industry.

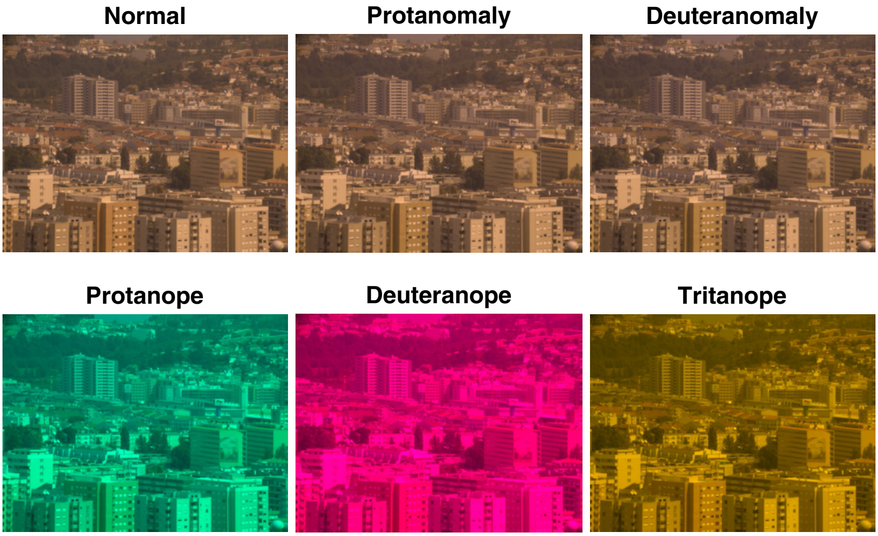

Figure 4. Simulated perceived colour images of a natural scene.

Recently, we proposed simple, fast, and inexpensive multispectral imaging solutions, some of which can be used in an uncontrolled outdoor environment under arbitrary illumination as well [25]. We, therefore, see the proposed methodology of using multispectral image promising for the simulation of accurate colour deficient images, and which leads to the design of more effective and accessible design of imaging solutions for wider audience.

We have presented the results of the simulation using severe cases of anomalous trichromacy and dichromacy. Standard or general spectral sensitivity of a specific type of colour deficient people provides perception of a scene by such people in general, whereas by knowing/measuring spectral sensitivity of a colour vision deficient individual, we can simulate an accurate colour deficient image as perceived by him/her.

The proposed method works well with the normal colour vision as well, where we can use either personalized or standard cone sensitivities from CIE (Commission Internationale de l'éclairage). In the context of universal design, the model can be built into an imaging system so that the system can automatically adapt to any individual (whether with normal colour vision or colour vision deficiency) by using the cone sensitivity data as a parameter.

7. Conclusion and perspectives

This paper has presented a method of simulating colour vision deficiency using a multispectral image. As simple and cost effective multispectral imaging technology getting prevalent, the proposed method becomes feasible and effective. Because of the inherent capability of spectral imaging, the method can produce accurate colour compared to traditional model-based techniques. This leads to more effective universal design for better and wider accessibility by the colour vision deficient people.

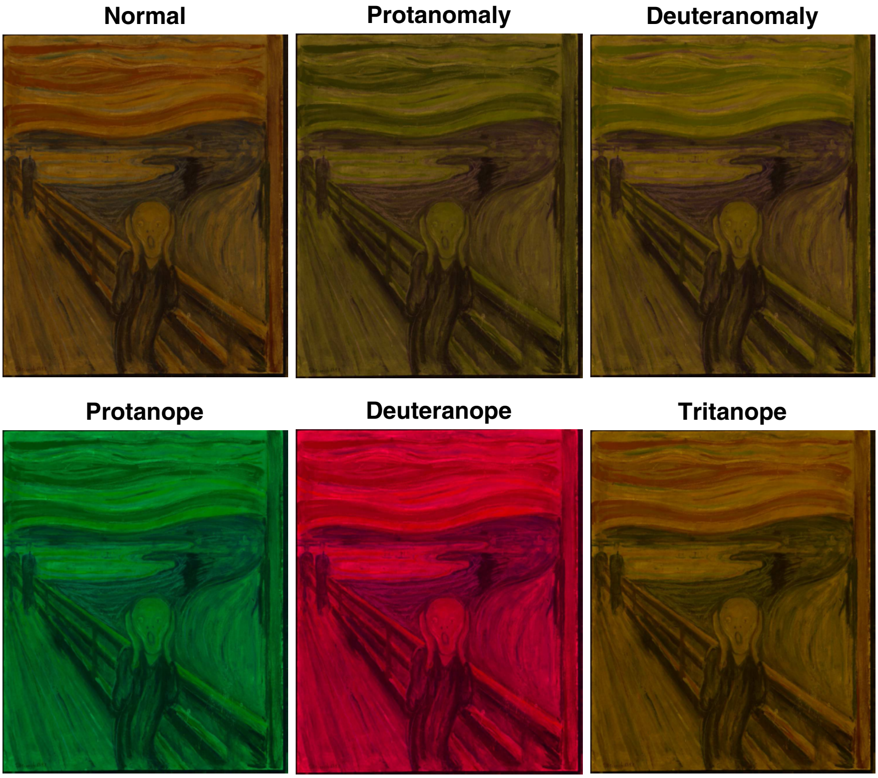

Figure 5. Simulated perceived colour images of the Scream painting.

As a future work, effectiveness of the methodology could be validated through a psychophysical experiment involving both normal and colour vision deficient individuals.

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