A framework and methodology for spectral color vision deficiency imaging

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ABSTRACT

People with color vision deficiency (CVD) face difficulties in everyday life and may get frustrated when they miss some of the important features in an image because of their inability to perceive differences between certain colors that can be distinguished by normal color vision people. This can affect access to education and choice in their career. In order to help millions of people affected by color blindness worldwide, a method known as daltonization is used, which tries to modify colors in a photographic image in order to increase the color contrast and bring back the missing features, thus improving the accessibility of the images in terms of retrieving information content for CVD people. A daltonization algorithm to work successfully, accurate conversion of a color image to a corresponding CVD image is vital. Many CVD simulation methods have been proposed, and most of them rely on color appearance theories and models that are imperfect. In addition, these methods are based on a generalization of CVD models and types. Moreover, color imaging has well-known limitations like environment dependency, metamerism problem, and it is limited to the visual spectrum. Since spectral imaging addresses these limitations effectively, spectral imaging-based simulation of CVD can produce individualized and more accurate results. In this paper, we present a framework for spectral image-based CVD imaging, which we call spectral CVD imaging, which can acquire an accurate personalized CVD image of a scene real-time under an uncontrolled illumination condition.

Keywords: *color vision deficiency (CVD), color blindness, simulation, spectral CVD imaging, framework*

1. INTRODUCTION

Color blindness or color vision deficiency (CVD) is an anomaly or defect in a person's vision system that causes the person not to be able to enjoy the full-color world as do the normal vision people. Because of the anomaly, people with CVD cannot perceive the difference between certain colors and can miss some of the important features in an image. For example, some CVD people may not be able to distinguish between colors of a traffic light, while some others cannot differentiate between tomato, lime, and orange. This can be extremely annoying and cannot only lead to frustration but also can affect access to education and choice in their career.

Depending upon type and number of defective cones among the three types of cone cells (L – Long or Red, M – Medium or Green, and S – Short or Blue) in our human vision system, CVD can be broadly categorized into three types: anomalous trichromat, dichromat, and monochromat. CVD 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 L, M, or S cone is affected, the condition is called protanomaly (Red-Weak), deuteranomaly (Green-Weak), and tritanomaly (Blue-Weak) respectively. CVD, where one cone does not function because of the absence of or reduced sensitivity are called dichromats and based on whether L, M, or S cones are affected; they are respectively called protanopia (Red-Blind), deuteranopia (Green-Blind), and tritanopia (Blue-Blind). There are people with both red-green color deficiency (both protanope and deuteranope). Those with 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 colorblind, i.e. they cannot see color at all. There are 7-10% of males who have some form of red-green color 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 (Wong 2011; color-blindness.com 2019). Different techniques are used to diagnose CVD such as Ishihara tests, color arrangement tests such as Fransword D-15 and D-100, anomaloscopes, and pseudo-isochromatic plates (Birch 1982). Altogether, there are millions of people worldwide affected by CVD, among them about 8% are men and 0.05% are women (colorblindawareness.org 2019). A study with multi-ethnic children found that the prevalence of CVD in preschool boys varies by ethnicity, with the highest prevalence in non-Hispanic white and lowest in black children (Xie et al. 2014).

Daltonization is a process which attempts to recolor (modifying the color of) a photographic image intended for color blinded people to increase the color contrast so as to bring back the missing features. Daltonization aims for improving the accessibility of the images in terms of retrieving information content for CVD people. Several daltonization methods and techniques have been proposed (Anagnostopoulos et al. 2007; Kim et al. 2012; Kotera 2012; Milic et al. 2015; Simon-Liedtke and Farup 2015). Almost all these daltonization methods use simulated CVD images. Since CVD image simulation is an important step before applying daltonization that determines the effectiveness of the daltonized image, this is our main focus in this work.

Many methods have been proposed for simulating CVD images. As most of these methods are based on CVD models, which rely on color appearance theories and models that are imperfect, these methods are not accurate. Moreover, these CVD models are based on trichromatic color imaging, which has several limitations such as environment dependency, suffers from metamerism, and limited to the visual spectrum. Therefore, the generated CVD images are far from perfect. Moreover, as most of the color vision deficiency models are generic models, they may not reflect the perceptual capabilities of an individual with a specific color vision deficiency.

Since spectral imaging mitigates the limitations of the trichromatic color imaging, and with the availability of fast, simple, and inexpensive multispectral imaging technologies, an accurate simulated color vision deficiency image can be generated for a given type of color vision deficiency using a spectral image (Shrestha 2016). As an extension to this work, this paper presents a framework for a real-time personalized CVD imaging under an uncontrolled environment (illumination condition). We have named this imaging technique as spectral color vision deficiency imaging.

After this introduction, Section 2 describes various related works on CVD image simulation. The proposed framework for a spectral CVD imaging is presented next in Section 3. Section 4 describes experiments, and present and discuss experimental results. Finally, Section 5 concludes the article.

2. CVD IMAGE SIMULATION

Among many CVD simulation methods proposed in the literature, most of the state-of-the-art methods are model-based that are derived from the observations from unilateral dichromats (people with dichromacy in only one eye, while the other eye has normal color vision). These observations found that both the normal and anomalous eyes perceive achromatic colors similarly (Graham and Hsia 1959; Judd 1945). An early technique by Meyer and Greenberg (Meyer and Greenberg 1988) mapped achromatic colors in approximate wavelengths of 475nm and 575nm for protanopia and deuteranopia, and 485nm and 660nm for tritanopia in XYZ color space and drew confusion lines representing directions along which there is no color variation according to dichromats color perception. The simulated deficient color is then defined by projecting the colors through the confusion lines on the reduced gamut. Brettel, Viénot, and Mollon (1997) obtained dichromatic colors by projecting the original color on the semi-planes in the LMS color space by constraining the direction of confusion lines to be parallel to the direction of the color spaces axes L, M, or S, depending on whether the dichromacy type is protanopia, deuteranopia, or tritanopia respectively. These techniques produce reasonably good results for dichromacy; however, they are not usable for anomalous trichromacy. Jim (2019) has provided a similar simulation model based on sRGB-LMS conversions.

Yang et al. (2008) proposed a simulation technique for anomalous trichromacy, based on the conversion of colors from RGB color space corresponding to a typical CRT monitor to anomalous LMS, and then converting back from LMS to RGB space. Gustavo Mello Machado (2010) found that the simulated images from this technique contain colors that are not the ones perceived by individuals with color vision deficiency. As a solution, he proposed a physiologically-based model based on the two-stage opponent color model of human color vision, which he claimed to perform better in terms of preserving achromatic colors and simulating both anomalous trichromacy and dichromacy (Ingling and Tsou 1977).

All the CVD models described are based on general models hence may not reflect the perceptual capabilities of an individual with CVD. Flatla and Gutwin (2012) proposed an empirical model-based approach for a more accurate color representation of what a particular person with CVD actually sees. A physiologically-based CVD simulation model has been proposed which claimed to consistently handle normal color vision, anomalous trichromacy, and dichromacy in a unified way (G. M. Machado, Oliveira, and Fernandes 2009). Both these models are still based on color imaging model, they suffer from all the limitations of color imaging.

To address the limitations of color imaging-based CVD image simulation, spectral imaging-based CVD image simulation method has been proposed (Shrestha 2016). This work has been extended further hereby incorporating real-time CVD image acquisition capability.

3. PROPOSED FRAMEWORK AND METHODOLOGY FOR SPECTRAL CVD IMAGING

Shrestha and Hardeberg (2014) proposed a novel a concept and methodology for spectral imaging, named as spectrogenic imaging, which can acquire a spectral image of a scene under an arbitrary illumination condition. A spectrogenic imaging system is built with a 6-band camera system that acquires two images of a scene, a normal RGB and a filtered RGB. The illuminant under which an image is captured is estimated using a chromagenic based algorithm (Finlayson, Hordley, and Morovic 2005; Shrestha and Hardeberg 2012a), and the system is calibrated automatically using the estimated illuminant. A spectral reflectance image of the scene is then estimated using an appropriate spectral estimation method. The proposed spectral CVD imaging use this spectrogenic imaging system in order to generate an accurate simulated CVD image of the scene under the given illumination condition for an individual CVD person having individualized cone sensitivities using the spectral reflectance image (Shrestha 2016). Figure 1 illustrates a complete framework and workflow for the proposed spectral CVD imaging.

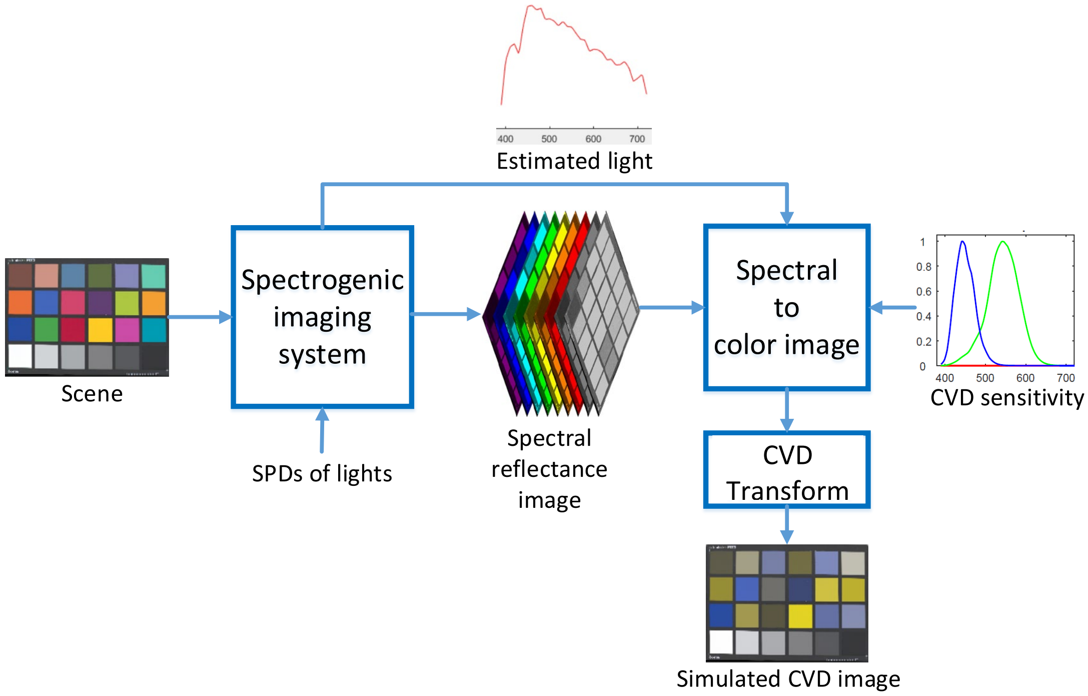

Figure 1. Schematic diagram of the proposed framework for spectral CVD imaging. The diagram shows SPD of D65 illumination and LMS sensitivities (Stockman and Sharpe 1999) for a protanope with a missing S-cone, as an example.

The spectral image-based simulated CVD images from Shrestha (2016) simply generates a simulated color image for a given CVD type using a standard color and spectral imaging model equations. This results in greenish, pinkish, and yellowish images in cases of protanope, deuteranope, and tritanope respectively, which are not correct. Protanomaly and deuteranomaly images can also be refined further. This is done by adding a CVD transformation step in the CVD imaging framework. In this step, the color image generated from the spectral image is transformed into a simulated CVD image, where each channel of the CVD image is obtained as a linear combination of the three channels. Weights for the linear combination can be calculated by using certain constraints from the fact that some colors perceived in a CVD type remain the same as the colors perceived in normal color vision. Let $\boldsymbol{Ci} = [ci_{\mathrm{l}},\ ci_{\mathrm{m}},\ ci_{\mathrm{s}}]^{\mathrm{T}}$, where $i = \{1, 2, 3\}$ denote the LMS color values of the three matching colors generated for a CVD in a vector notation and $\boldsymbol{Ci}^{\mathrm{n}} = [ci_{\mathrm{l}}^{\mathrm{n}},\ ci_{\mathrm{m}}^{\mathrm{n}},\ ci_{\mathrm{s}}^{\mathrm{n}}]$ the corresponding color values for the normal color vision, the CVD transformation can be modeled by the following matrix equation.

$$\begin{bmatrix} c1_{\mathrm{l}}^{\mathrm{n}} & c2_{\mathrm{l}}^{\mathrm{n}} & c3_{\mathrm{l}}^{\mathrm{n}} \\ c1_{\mathrm{m}}^{\mathrm{n}} & c2_{\mathrm{m}}^{\mathrm{n}} & c3_{\mathrm{m}}^{\mathrm{n}} \\ c1_{\mathrm{s}}^{\mathrm{n}} & c2_{\mathrm{s}}^{\mathrm{n}} & c3_{\mathrm{s}}^{\mathrm{n}} \end{bmatrix} = \begin{bmatrix} w_{\mathrm{ll}} & w_{\mathrm{lm}} & w_{\mathrm{ls}} \\ w_{\mathrm{ml}} & w_{\mathrm{mm}} & w_{\mathrm{ms}} \\ w_{\mathrm{sl}} & w_{\mathrm{sm}} & w_{\mathrm{ss}} \end{bmatrix} \begin{bmatrix} c1_{\mathrm{l}} & c2_{\mathrm{l}} & c3_{\mathrm{l}} \\ c1_{\mathrm{m}} & c2_{\mathrm{m}} & c3_{\mathrm{m}} \\ c1_{\mathrm{s}} & c2_{\mathrm{s}} & c3_{\mathrm{s}} \end{bmatrix} \tag{1}$$

Denoting the left matrix in this equation as $\mathbf{C}^{\mathrm{n}}$, the weights matrix in the middle as $\mathbf{W}$, and the rightmost matrix as $\mathbf{C}$, the weights can be calculated using the equation, $\mathbf{W} = \mathbf{C}^{\mathbf{n}}\mathbf{C}^{-1}$. We use white, green and blue as the matching color constraints for protanomaly, and white, red, and blue for deuteranomaly. In case of the dichromats, one channel output results in zeros as they have one cone missing. The missing channel output is calculated as a linear combination of the other two channels. Therefore, we use just two matching colors constraints in Equation 1. For protanope and deuteranope, white and blue, and for tritanope, white and red are used as the matching color constraints (Kulesza 2018). The third color $\mathbf{C3}$ is set to $[1,\ 0,\ 0]^{\mathrm{T}}$ for protanope, $[0,\ 1,\ 0]^{\mathrm{T}}$ for deuteranope, and $[0,\ 0,\ 1]^{\mathrm{T}}$ for tritanope; and $\mathbf{C3}^{\mathbf{n}}$ is set to $[0,\ 0,\ 0]^{\mathrm{T}}$ in all the three cases.

In order to display a simulated CVD image on a screen, the image is white balanced, then converted from the LMS space to standard XYZ color space using the Hunter-Ponter-Estevez transformation (Fairchild 2005), and then this image is finally converted to sRGB color space.

Since the spectrogenic imaging can be realized using different types of camera design and setup, such as using a stereo camera (Shrestha and Hardeberg 2012b) or using a custom spectral filter array (Shrestha and Hardeberg 2013), a spectral CVD imaging system can be realized easily using off-the-shelf cameras and by feeding an individualized or generic CVD cone sensitivities (standard ones for the people with normal color vision); and used in real practice.

4. EXPERIMENTS, RESULTS, AND DISCUSSION

A prototype 6-band stereo-camera based spectral imaging system built with a Fujifilm FinePix REAL 3D W1 stereo camera and Omega XF1078 filter in front of one of the camera lenses from Shrestha and Hardeberg (2014) is used. A hyperspectral image of bear and fruit gray images acquired under the blue light from Brainard (2004) is used for the simulated output spectral image from the spectrogenic imaging system under a standard CIE D65 illumination. This test image is chosen because it contains several different types of objects including a Macbeth ColorChecker (MCC), bear, fruits, and books. The resulting spectral image is then used to simulate the five different CVD images, protanomaly, deuteranomaly, protanope, deuteranope, and tritanope as discussed in Shrestha (2016), using the proposed spectral CVD imaging framework as described above. As tritanomaly is rare, it is skipped here. The white, red, green, and blue color patches in the MCC are used to calculate weights in the CVD transformation (Equation 1) step to generated simulated CVD images. Figure 2 shows the five simulated CVD images along with the normal vision color image resulted from the spectral CVD imaging system.

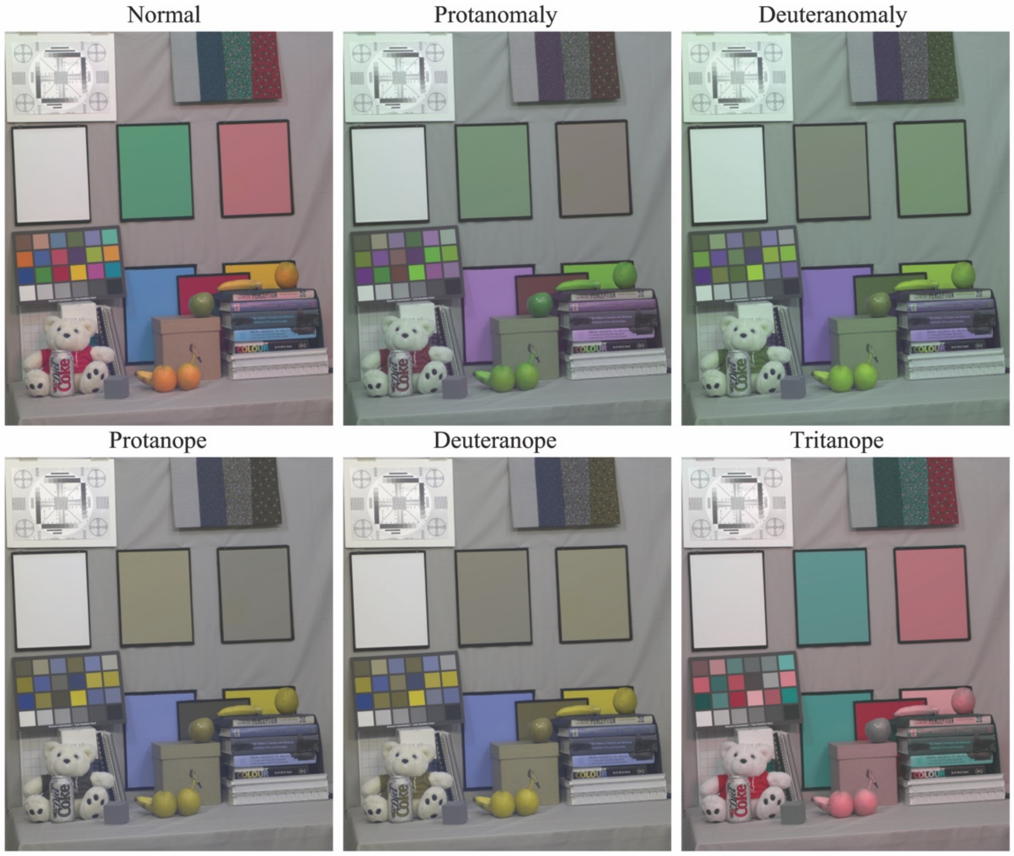

Figure 2. Simulated CVD images of the Bear and Fruit Gray image (Brainard 2004) in sRGB color space, generated from the spectral CVD imaging.

From the resulting simulated CVD images, we can see how people with different CVD face difficulty distinguishing some colors. It is hard to verify the accuracy of the simulated CVD images without psychophysical experiments with a number of people having different types of CVDs. However, we find that the resulting simulated images are similar to the results from the most widely used simulator Coblis-Color Blindness Simulator (color-blindness.com 2019). It is to be noted here that, the red, green, and blue colors used in the CVD transformation from the Macbeth ColorChecker are not pure primary colors. By using colors closer to pure primary colors, further improved results can be anticipated.

The main advantage of the proposed spectral CVD imaging is that a system based on the framework can acquire and generate a CVD image for an individual with a personalized CVD type, under an uncontrolled illumination condition in real-time by pre-calibrating and characterizing the system with custom cone sensitivities. Since the simulation is based on spectral imaging, we can anticipate more accurate simulation compared to a classic color imaging-based simulation. Also, having a spectral image, a simulated CVD image can be obtained under any given illumination. Moreover, the system can be incorporated with an in-built daltonization algorithm adapted to the personalized CVD type so that it can produce an enhanced image to minimize feature loss due to the CVD problem.

A limitation of the system is that the accuracy of estimation of illumination under acquisition depends on the richness of the dataset of spectral power distribution of light sources, which has the one close to the test illumination. Moreover, we assume that an individualized cone sensitivity is available to use it as a parameter in the system. However, in case of the unavailability of such data, the system can still be used with a standard cone sensitivity data for a specific type of CVD.

5. CONCLUSION

A spectral color vision deficiency imaging system based on the proposed framework and methodology can be used to acquire a simulated CVD image under an arbitrary illumination condition in real-time. Such a system can be built using off-the-shelf camera systems. The system can be customized or individualized for a person with a specific type of CVD by using his/her individual cone sensitivities, or by using cone sensitivities of a standard CVD type close to his/her. The system can be further extended with an in-built daltonization method for that particular CVD type to build a full-fledged camera system which can produce a daltonized image that brings back the missing features because of the CVD.

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