Color Vision Deficiency and Related Digital Adaptation Methods

Rong Ye — Darlington School
Yuanbo Jiang — Bishop Hendricken Catholic High School
Brian A. Barsky — UC Berkeley

Abstract

Suffering from color blindness, a significant percentage of population faces the difficulty of recognizing color-based information. In this paper, we analyze the basic characteristics and digital accommodation methods of color vision deficiency. First, the symptoms and cause of color vision deficiency are examined. Then different color models are introduced to simulate color vision deficiency. Finally, we evaluate current methods designed to accommodate digital images for color vision deficiency users.

Keywords Adaptive Technology, Color Vision Deficiency.

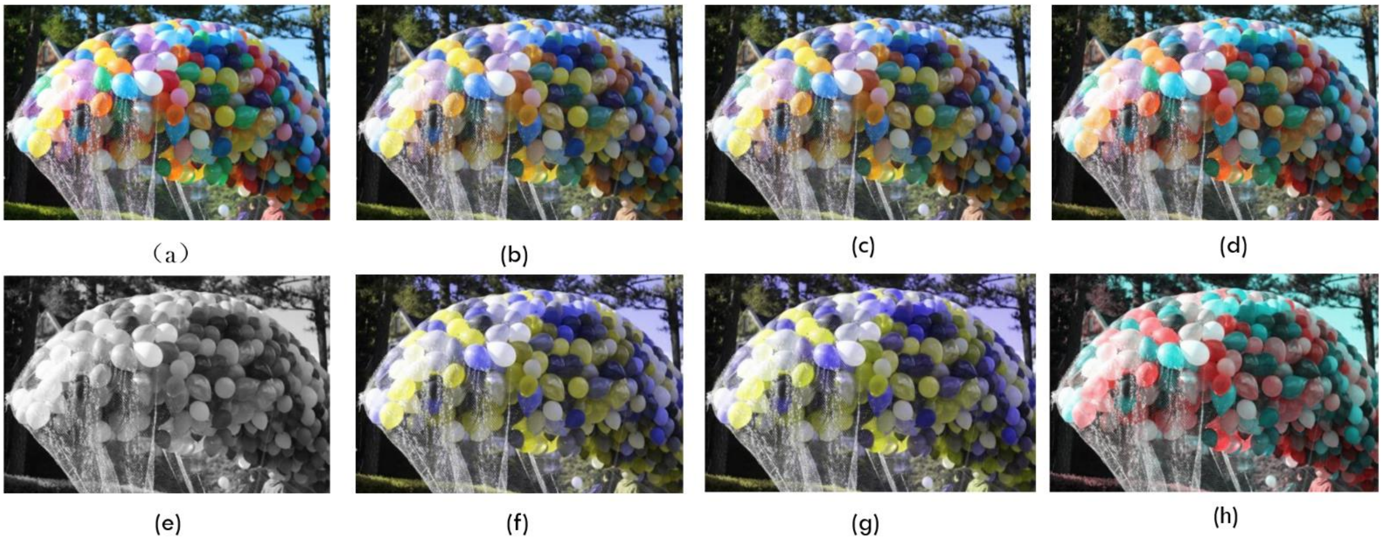

Figure 1: A digital image perceived by (a) normal people; (b) protanomaly patients; (c) deuteranormaly patients; (d) tritanomaly patients; (e) monochromacy patients; (f) protanopia patients; (g) deuteranopia patients; and (h) tritanopia patients.

1. Introduction

The study of color blindness has a remote history, as the first scientific paper about it was written in late eighteenth century by John Dalton. He discovered the red-green color-blind symptom of his own.

In the modern society, with the popularization of color printing and color display, the role of colors in designing and visual information conveyance has become increasingly prominent. However, color-deficient users view the colors differently from normal people and thus have trouble perceiving the information delivered by colors. For example, colors used to demonstrate contrast or highlight effect may seem alike to color-deficient users. Although such impediment caused by color vision deficiency is common, few digital documents or web-page are designed to be color-blind accessible. Colorblind users may find using color display devices frustrated.

Recent research has been conducted on the digital accommodation of color vision deficiency. Design guidelines for color-deficient users are proposed and several algorithms repainting the digital images are developed. In this paper, we compare such methods in their mechanisms and efficiency.

The rest of the paper is structured as follows: Section 2 introduces the color vision deficiency and its cause. Section 3 describes the color model using to simulate color vision deficiency. Section 4 and 5 review current methods developed to accommodate digital images for colorblind users. The last section concludes the paper.

2. Color Vision Deficiency

Color vision deficiency (CVD) is one of the most universal congenital diseases. Such a disorder affects 8% male and 0.5% female worldwide. Patients are reportedly troubled with their inability to distinguish certain colors.

Human vision system perceives light through two receptors in the retina: rod cells which detect the intensity of light and cone cells which distinguish different colors of light. Cone cells are classified into three types according to the different ranges of light wavelength they are sensitive to. L-cones are sensitive to long wavelength light, M-cones are sensitive to middle wavelength light and S-cones are sensitive to short wavelength light. The mixing signals of three cone cells constructs the gamut of human color vision.

Color vision deficiency is caused by the loss of cone cells or shifts of sensitivity peaks. CVD is categorized into three broad classes: monochromatism which only one type or none of the cones exists, dichromatism which only two types of cones are available and anomalous trichromats which all three types of cones exist but some have shifted peaks. Furthermore, dichromatism exists in three types, tritanopia, deuteranopia and protanopia, according to the loss of S-cones, M-cones or L-cones. Anomalous trichromatism also exists in three types, tritanomaly, deuteranomaly and protanomaly, depending on malfunction of S-cones, M-cones or L-cones.

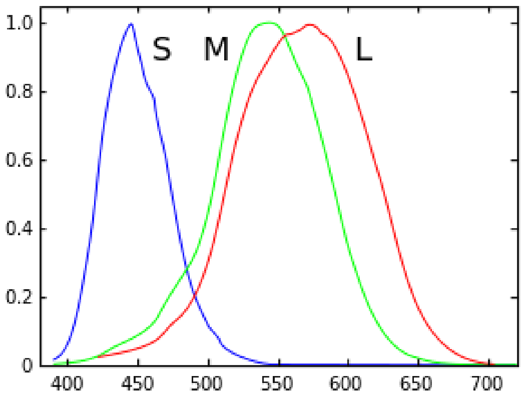

Figure 2: Graph of cone's response of normal people.

3. Modeling CVD

Modeling CVD is addressed as the foundation of simulating view of CVD patients and further research. In [7], Gary W. Meyer brings up a problem in synthesizing the picture as it appears to dichromats. Meyer claims that, although people with normal color vision may accept the reproduction of a scene to be a simulated picture in dichromats' vision, it is impossible to prove that the simulated colors are the same as perceived by colorblind people. Thus, it is not practical for individuals with normal vision to state what exact color CVD patients see. As it seems difficult for normal people to have the accurate data about the vision of CVD patients, some people are found to be Unilateral Tritanopia [10], patients with one dichromatic eye and one normal eye. From their color matching measurements, the hues perceived by dichromats can be revealed.

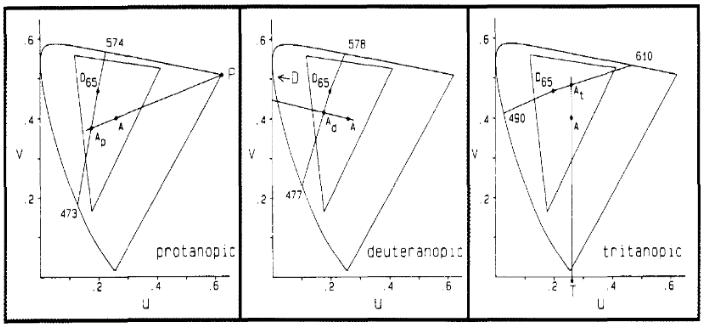

Figure 3: Confusion line and major axis in the color space.

In the CVD model proposed by Meyer in [7], Meyer applies the idea of "confusion line" and "major axis" in the XYZ color space. In [2], Farnsworth addresses the transformation of hue circuit for normal color vision into a hue line in the vision of protanopes and deuteranopes. The endpoints of the line are approximately 470nm which is yellow and approximately 575nm which is blue. Farnsworth thus defines such line as a "major axis" on a chromaticity diagram. The confusion line was described by J.C. Maxwell in 1855, defined as the line in the CIE diagram between two colors which a colorblind person cannot differentiate. Such line will connect all colors which are indiscernible to the individual. The intersections between the major axis and each confusion line indicate the color perceived by the dichromat.

More recently, simulating the vision of CVD in digital images is possible by modeling CVD in LMS color space. In [7], the model of computing LMS tristimulus values is

$$
\begin{aligned}
S &= \int E(\lambda)\bar{s}(\lambda)d\lambda \\
M &= \int E(\lambda)\bar{m}(\lambda)d\lambda \\
L &= \int E(\lambda)\bar{l}(\lambda)d\lambda
\end{aligned}
$$

where E[λ] is the light power spectral density function and s(λ), m(λ), and l(λ) are the fundamental spectral sensitivity functions for short, medium, and long wavelengths respectively. A CVD simulating projection algorithm described in [3] replaces the tristimulus values with a reduced CVD stimulus surface. Thus the simulation of CVD can be achieved by three steps: 1) convert the RGB data to LMS values; 2) apply the projection in [3] to the LMS values and 3) convert the LMS coordinates back to RGB values.

4. Digital Accommodation

Several digital adaptation methods [1,4,5,6,7,8,9,11] have been proposed to accommodate CVD users in digital displays. These methods are termed as pre-publication methods and post-publication methods in [6], corresponding to design-assisted techniques and recoloring algorithms.

4.1 Pre-publication Methods

The Fransworth-Munsell 100-hue test and the models of Color Vision Deficiency described in previous sections contribute to the color design guidelines, a typical approach in computer graphics displays for color-defective users. The guidelines attempt to improve the perception and differentiability of chromaticity of color-defective users.

In [7], Gary W. Meyer and Donald P. Greenberg offer a color design guideline which uses two color scales that lie approximately orthogonal to the chromaticity confusion lines. Using such color scales allows dichromats to distinguish the colors more clearly. Furthermore, the color scales for protanopia and deuteranopia have the same chromaticity loci and can also work for the less restrictive trichromats. Thus, the color design guideline of Meyer and Greenberg also provides a single set of colors that can be differentiated by all types of color-deficient users.

An alternative approach provided by Christine Rigden in [1] is the use of a Web-safe palette for colorblind users. A 216-color Web-safe palette is generated by simulating the colors perceived by protanopes and deuteranopes. The Web-safe palette can be applied in 2 ways: it can be applied to images to simulate how they appear in the perception of protanopes and deuteranopes, or be employed by Web designers to select safe color combinations for the Website color scheme.

However, problems with pre-publication methods do exist. First, due to the various types of CVD, accommodating every CVD user can be intricate and strenuous. Second, as the colors displayed on every computer monitor are not completely identical, the effectiveness of color accommodation depends on the color accuracy of the devices. Third, as most systems run 8-bit color, the 216-color Web-safe palette is rarely applied.

4.2 Post-publication Method

In [4] and [11], an adaptation technique for color vision deficiency in the MPEG-21 Digital Item Adaptation is proposed. The proposed resource adaptation for CVD works differently for severe CVD and mild CVD. For severe CVD, with the goal of improving the color information accessibility, the resource adaptation modifies in HSI color space the hue and saturation of colors which are not discernible to the severe CVD users according to their types of CVD. As for mild CVD, the resource adaptation aims at enabling mild CVD users to see the original color by highlighting the colors in their insensitive color vision ranges.

The work in [8] and later [9] proposes a more general method. An abstracted image model is designed to divide the image into different color regions. The relations between different color regions are defined in two types: “included” relation that one color region is completely encompassed by another region and “even” relation that two color regions are contained by the same region. In [8], the relations are analyzed by the distance between regions and the HTML description of a web-page. In [9], the regions are segmented by using the median cut method to quantize color spaces which are then categorized. Then a fitness function, which weights the spectral color differences and brightness differences in Luv color space, is performed to modify colors. The colors are thus modified by solving the optimization and interpolation. Both computer simulations and psychophysical assessments revealed an improvement of colorblind users' abilities to discriminate colors using the proposed scheme.

In [6], an algorithm is introduced to map colors for color-deficient viewers in accordance with the World Wide Web Consortium evaluation criteria. The algorithm has four steps. 1) A set of representative colors, called key colors, are selected from the image by sampling the difference histogram. 2) The target distance, composed of brightness difference and color difference in the original image, are computed using the color visibility evaluation standards of World Wide Web Consortium. 3) The optimization problem is then solved such that the target distance error, gamut error for colors mapped outside human gamut, and penalty for mapping special colors such as white incorrectly are minimized. 4) The remaining colors are interpolated from the corrected key colors using Shepard's method, an inverse-distance weighting interpolation. For protanopes and deuteranopes, this algorithm essentially recolors red-green variation with blue-yellow and light-dark; for tritanopoes, the blue-yellow variation is replaced with red-green and light-dark.

In [5], a disambiguation framework for colorblind users named SmartColor is described. The SmartColor framework incorporated author's annotations about his or her intended color effects which guide the repainting of a document or an image. By formulating the color effects mathematically in a set of constraints, the SmartColor framework is able to project the constraint onto the deficient color space perceived by colorblind users. The constraints are then resolved to repaint the document or image with an optimal color scheme which effectively delivers the color effects to colorblind users. The constraints consist of four color effect components: 1) color difference between two colors; 2) color consistency; 3) distinguishability of an element's color from its adjacent elements; and 4) invariance of special colors such as white or colors that are mentioned with their names in the document. Parameters indicating the author's desirability of each component are used in the optimization. Since the resulting function is multi-variant and non-linear, the optimization for SmartColor requires the use of non-linear optimizer simulated annealing algorithm and a small number of colors.

5. Conclusion

This paper makes a thorough examination of color vision deficiency, including its symptoms and cause. The principles and methods of modeling CVD are introduced as the foundation for image adaptation for CVD users. Then several methods addressing digital adaptation for CVD from previous work are analyzed. However, most methods are limited by the computational cost and flexibility for different types of CVD. Thus the future work should further investigate the maximization of efficiency of optimization.

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