A Model for Simulation of Color Vision Deficiency and A Color Contrast Enhancement Technique for Dichromats

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Abstract. *We present the first model in the literature for simulating human color perception that consistently accounts for normal color vision and for the most prevalent cases (99.96% of all cases) of color vision deficiency. We also present an automatic image-recoloring technique for enhancing color contrast for dichromats that is up to two orders of magnitude faster than previous approaches and, due to its time coherence, is the first technique suitable for real-time video recoloring for dichromats. Finally, we introduce a metric for estimating the loss of color contrast experienced by individuals with color vision deficiency (CVD), or resulting from image recoloring. Together, these results contribute for a better understanding of CVD and for improving the quality of life of the affected individuals.*

Keywords: Models of Color Vision, Color Perception, Simulation of Color Vision Deficiency, Image and Video Recoloring, Visualization.

1. Introduction

Color Vision Deficiency (CVD) affects people's ability to distinguish certain colors. Estimates indicate that approximately 200,000,000 (two hundred million) individuals worldwide are affected by some kind of CVD, and currently there is no clinical or surgical treatment for this kind of condition. Individuals with CVD face difficulties to perform color-related tasks, which interfere with their personal and professional lives. Figure 1 illustrates this situation, where the reference image on the left shows an example of medical visualization in which colors represent tissue density. The image on the center depicts how the reference image is perceived by a class of individuals with CVD. Note the loss of color contrast, which results in the loss of important information. This example illustrates a recurring and challenging situation faced by these individuals in their daily activities.

Human normal color vision (also called normal trichromacy) requires three kinds of retinal photoreceptors with peak sensitivity in the long, medium and short wavelengths portions of the visible spectrum. Such photoreceptors are called L , M , and *S cones*, respectively. The spectral response of each kind of cone is defined by the specific type of photopigment it contains. Natural variations of some proteins that constitute a given photopigment may shift its sensitivity to a different band of the spectrum. In this case, the condition is called *anomalous trichromacy*. *Dichromacy* is caused by the absence of one of the photopigments and can be classified as *protanopia*, *deuteranopia*, or *tritanopia*, if the missing photopigment is the one associated in normal color vision with the L, M, or S cones, respectively. Anomalous trichromacy and dichromacy are the most common types of CVD, covering more than 99.99% of the cases.

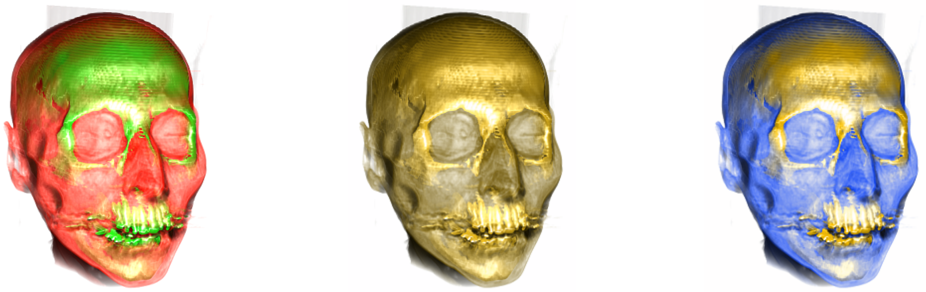

Figure 1. Example illustrating the difficulties faced by individuals with CVD. (left) A medical-visualization image used as reference. (center) Simulation of how deuteranopes perceive the reference image. (right) Recolored image as perceived by deuteranopes, recovering the loss of color contrast. These images were simulated and recolored using the techniques presented in this thesis.

1.1. Contributions

This thesis presents three main contributions related to color vision deficiency: a model for simulating human color perception, an automatic image-recoloring technique to enhance color contrast for dichromats, and a metric for estimating the loss of color contrast experienced by individual with CVD or resulting from image recoloring.

Our physiologically-based model for simulating human color perception is the first model in the literature capable of consistently simulating the perception of normal-color-vision individuals as well as the most prevalent cases of CVD in a unified way. It handles approximately 99.96% of all CVD cases, while previous approaches only handle about 27.46%. Our model was validated by a user experiment, and a paper describing it, entitled *A Physiologically-based Model for Simulation of Color Vision Deficiency* [Machado et al. 2009], was published in the *IEEE Transactions on Visualization and Computer Graphics*, the most prestigious journal in the visualization community.

Our second contribution is an automatic image-recoloring technique for enhancing color contrast for dichromats. Our solution has a linear cost in the number of pixels and, for typical images sizes, is up to two orders of magnitude faster than previous approaches. It is also the first technique capable preserving temporal coherence and performing high-quality video recoloring for dichromats in real time. In this context, we also introduced a third contribution: a metric for estimating the loss of color contrast experienced by individuals with color vision deficiency, or resulting from image recoloring. A paper describing these two contributions, entitled *Real-Time Temporal-Coherent Color Contrast Enhancement for Dichromats* [Machado and Oliveira 2010], was published in the *Computer Graphics Forum* journal, one of the most important in the field.

GPU implementations of both the simulation model and the recoloring technique were successfully integrated with a visualization system, providing practical validation of our results. Figure 1 (right) shows a result of the proposed recoloring technique for enhancing color contrast for dichromats. This image corresponds to the perception of a deuteranope for the image shown on Figure 1 (left). Note the recovery of color contrast by comparing it to Figures 1 (left) and (center).

Due to space restrictions, this article cannot present all the details of the developed simulation model, recoloring technique, and image-contrast metric. The complete thesis work [Machado 2010] and the homepages of both publications [Machado et al. 2009, Machado and Oliveira 2010] can be found in `http://www.inf.ufrgs.br/~gmmachado`. We suggest that the readers watch the videos available in these homepages for more intuitive descriptions and examples of applications of the developed techniques.

2. Simulation

Despite the relevance of understanding how individuals with CVD perceive colors, little had been done in terms of simulating their perception for normal trichromats. In particular, none of the previous approaches is capable of handling both dichromacy and anomalous trichromacy. The first techniques that simulate the perception of individuals with dichromacy [Meyer and Greenberg 1988, Brettel et al. 1997] were developed based on the reports of *unilateral dichromats*, *i.e.*, individuals with one dichromatic eye and one normal trichromatic eye. According to these reports, achromatic colors as well as two other hues are perceived similarly by both eyes. Previous techniques mapped these colors to two semi-planes in some color space, and defined the simulation technique as the projection of the original colors on these semi-planes. This approach, however, cannot be used to simulate anomalous trichromacy.

2.1. The Model for Color Perception Simulation

Our physiologically-based model for color perception simulation treats CVD as changes in the spectral absorption of the cones' photopigments. While CVD is essentially modeled at the retinal photopigment stage, the opponent-color stage is crucial for producing the correct results and cannot be underestimated. For this, our approach uses Ingling and Tsou's model [1977] (Figure 2 left) for representing the opponent-color stage.

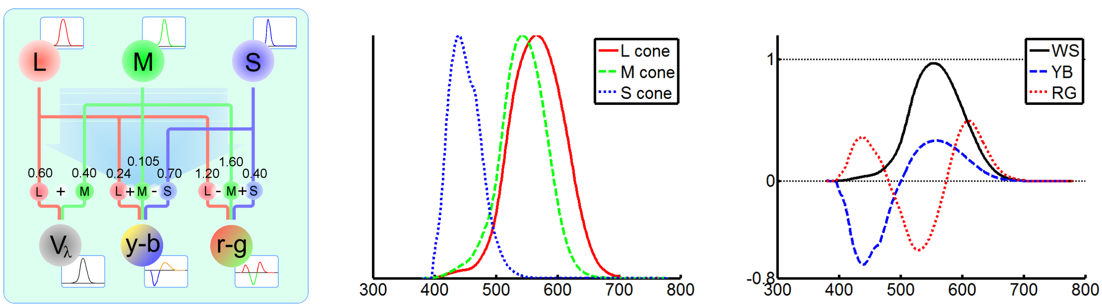

Figure 2. (left) Two-stage model of human color vision. The output of the photoreceptor stage (L, M and S cones) is linearly combined in the opponent stage (V_λ, $y - b$, and $r - g$ nodes). (center) Cone spectral sensitivity functions for an average normal trichromat (after Smith and Pokorny [1975]). (right) Spectral response functions for the opponent channels of the average normal trichromat according to Ingling and Tsou's [1977] model.

A transformation from an RGB color space to an opponent-color space is obtained by projecting the spectral power distribution functions of the RGB primaries onto the appropriate set of opponent functions $WS(\lambda)$, $YB(\lambda)$, and $RG(\lambda)$ (Figure 2, right), which define the opponent-color space for either normal trichromats, for anomalous trichromats, or for dichromats. These projections provide the elements of a matrix that directly maps RGB to the opponent-color space:

$$\Gamma = \begin{bmatrix} WS_R & WS_G & WS_B \\ YB_R & YB_G & YB_B \\ RG_R & RG_G & RG_B \end{bmatrix}. \quad (1)$$

Let Γ_{normal} and Γ_{CVD} be the matrices that map RGB to the opponent-color space of a normal trichromat and of a given class of CVD, respectively. The simulation, for a normal trichromat, of the color perception of this class of CVD, is obtained with Equation 2. As shown in the thesis, this general solution applies to the simulation of 99.96% of all cases of color vision deficiency.

$$\begin{bmatrix} R_s \\ G_s \\ B_s \end{bmatrix} = \Gamma^{-1}_{normal}\,\Gamma_{CVD} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (2)$$

3. Recoloring

Several researchers have investigated the problem of image-recoloring for dichromats. The most relevant techniques [Rasche et al. 2005, Kuhn et al. 2008] are optimization-based approaches that treat image-recoloring as a dimensionality-reduction problem in an approximately perceptually uniform color space (*e.g.*, CIE $L^*a^*b^*$). They approximate the color gamut of dichromats with a plane and attempt to preserve the distances between all pairs of colors. Kuhn et al. [2008] uses a mass-spring system to optimize color distances on the plane while preserving color naturalness. Despite being about three orders of magnitude faster than previous techniques, Kuhn et al.'s approach still does not achieve real-time performance. A recent study [Lee and dos Santos 2011] published after this thesis dealt with image-recoloring using fuzzy logic.

3.1. The Recoloring Algorithm for Dichromats

Our recoloring solution is based on the key observation that, whenever dichromats experience some significant loss of color contrast, most of this contrast can be recovered by working on a perceptually uniform color space, and orthographically projecting the original colors onto a plane that minimizes contrast loss (in a least-squares sense). The coordinates of these projections then become the new color coordinates on the reduced (2D) color gamut of the dichromat. Figure 5.3 summarizes this process, which consists of the following steps:

1. Estimation of the vector v_{ab} that represents the direction that maximizes contrast loss in the CIE $L^*a^*b^*$ chromaticity plane, and
2. Orthographic projection of the original colors onto the plane defined by v_{ab} and the lightness (L^*) axis. The projection on such a plane minimizes contrast loss. The projected color coordinates are then rotated around L^* to align themselves to the plane of the dichromat, and the resulting colors are used to recolor the image.

In order to guarantee temporal coherence, the algorithm checks and corrects for abrupt changes in the sense of v_{ab}. Figure 4 compares the results of our recoloring technique (*Our Recolor*) against the ones obtained using Kuhn et al.'s regular (*Kuhn's Recolor*) and exaggerated-contrast (*Kuhn's Exag.*) recoloring techniques. Our results are not only superior, but our technique is up to two orders of magnitude faster.

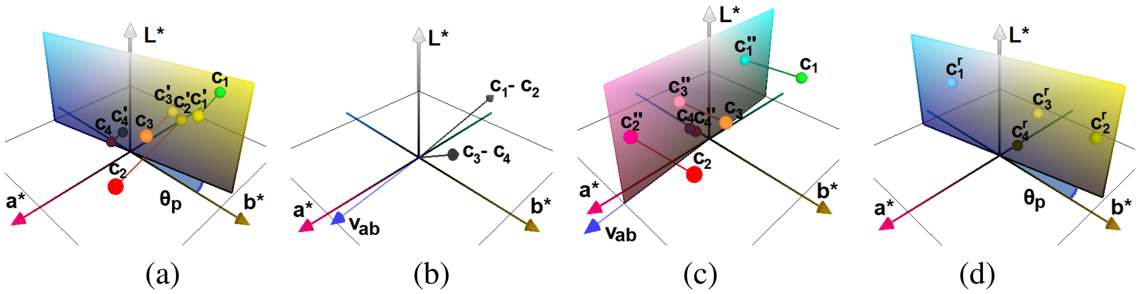

Figure 3. The steps of our recoloring algorithm. (a) Colors c_1 to c_4 are perceived by a dichromat as c'_1 to c'_4, respectively (their projections on the dichromat's gamut plane). The relative loss of contrast experienced by a dichromat for a pair of colors (c_i, c_j) is given by $l_{(c_i,c_j)} = (\|c_i - c_j\| - \|c'_i - c'_j\|)/(\|c_i - c_j\|)$, which happens along the direction $\vartheta_{ij} = c_i - c_j$. (b) Direction v_{ab} (shown in blue) that maximizes the loss of local contrast (in a least-square sense). (c) Projection of the original colors on the plane defined by v_{ab} and L^*. (d) Final colors obtained after rotating the projected colors c''_k in (c) around L^* so that they align with the dichromat's plane.

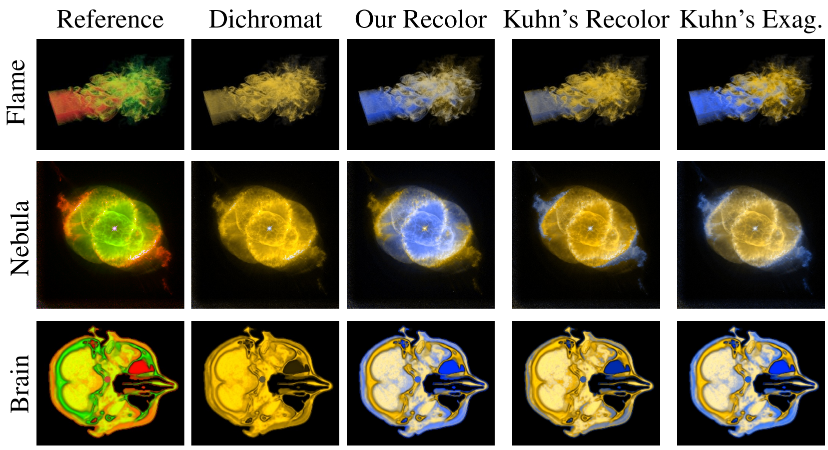

Figure 4. Comparison of the results produced by our recoloring technique and by Kuhn et al.'s [2008] for a set of scientific and medical visualization images. The *Dichromat* column shows the simulated perception of dichromats for the corresponding *Reference* images.

4. Conclusion

Color vision deficiency impacts the professional and personal lives of approximately two hundred million individuals worldwide. It is essential to fully understand this condition and provide solutions that contribute to improve the quality of life of the affected individuals and promote their access to new technologies. This thesis contributes some important steps towards these goals. More specifically, it introduced the first model of human color perception to correctly simulate both normal color vision, anomalous trichromacy, and dichromacy in a unified way, handling about 99.96% of all cases of color vision deficiency. It also presented an automatic image-recoloring technique for dichromats, which is the first to perform high-quality recoloring in real-time and also the first to guarantee temporal coherence. We also developed a metric for estimating the loss of color contrast experienced by individuals with CVD, or resulting from recolorings.

We demonstrated the effectiveness of these techniques by integrating them into a real-time visualization application and showing how they can significantly improve human-computer interface for individuals with CVD. Our simulation model helps normal-color-vision designers to better understand the limitations of individuals with CVD, which results in more effective designs for wider audiences. In turn, our real-time recoloring technique gives individuals with CVD the ability to explore color-related contents autonomously, reducing the ambiguity that often imposes significant challenges to these individuals.

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