IMAGE RECOLORING FOR COLOR-DEFICIENT VIEWERS

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ABSTRACT

Color is relied heavily upon when conveying information in a visual manner, in many, if not all, socio-cultural groups, day-to-day activities, and fields of work. Any misrepresentation or misperception of colors can cause issues stemming from the incorrect interpretation, and in some cases complete absence of information, with impact ranging from negligible inconveniences, such as an unpleasant aesthetic impression, to more serious consequences, especially in cases where information is primarily coded by color (e.g. warning labels, or traffic lights). This, in conjunction with the current spread of digital imagery, has led to the study and development of methods of recoloring images so as to allow color deficient viewers to perceive them as accurately as possible, and deliver a more complete visual experience.

KEYWORDS: *Image Recoloring, Color Deficient Viewer, Color Perception, Trichromacy, Dichromacy, Monochromacy, Protanomalous, Deuteranomalous, Tritanomalous, Protanopic, Deuteranopic, Tritanopic.*

INTRODUCTION

Studies[1]–[4] estimate that around 3% of the population, specifically between 2% and 10% of males and between 0.1% and 1.5% of females, experience a form of color deficiency, commonly referred to as color blindness, amounting to 200 million persons worldwide. While color blindness can be acquired as a result of an illness or injury, in most cases it is congenital, and affects individuals of all demographics.

COLOR SPACES

In broad terms, processing colored imagery for the use of deficient viewers can be described as remapping to a gamut of lower dimension, while aiming to preserve, and in certain cases enhance, the perceptual differences between colors. As such, many papers in this area of research make use of the **CIE-L*a*b*** color space to facilitate the assessment of perception, as well as to ensure a device independent representation. CIE-L*a*b* also allows the use of Euclidean distances between points to represent relative perceptual differences, and proves particularly relevant when discussing dichromacy.

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The **CIE-L*a*b*** standard, a successor to Hunter's Lab color space [5], is a simplified mathematical approximation of an uniform color space [6], where lightness or luminance is handled by the $L*$ component, $a*$ handles the red–green axis, and $b*$ the blue–yellow axis. Of the three axis, only L* is standardized to span from 0 to 100, the remaining two are theoretically unbounded, though in practice dependent on the medium on which colors will be displayed. In order to better replicate the perception of a real eye, the CIE-L*a*b* system has nonlinear relations between its components, which means conversion to and from other color spaces isn't always straightforward. Generally speaking, the transformation can be formalized as:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right) \quad \text{where} \quad f(t) = \begin{cases} \sqrt[3]{t} \; if \; t > \delta^3 \\ \frac{t}{3\delta^3} + \frac{4}{29} \; otherwise \end{cases} \text{and } \delta = \frac{6}{29}$$

$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

For the values X_n, Y_n, and Z_n, a reference white point is needed[6], which is directly related to the (theoretical) light source taken into account. Values for certain lighting conditions have been determined by researchers [7],[8].

COLOR PERCEPTION FOR DEFICIENT VIEWERS

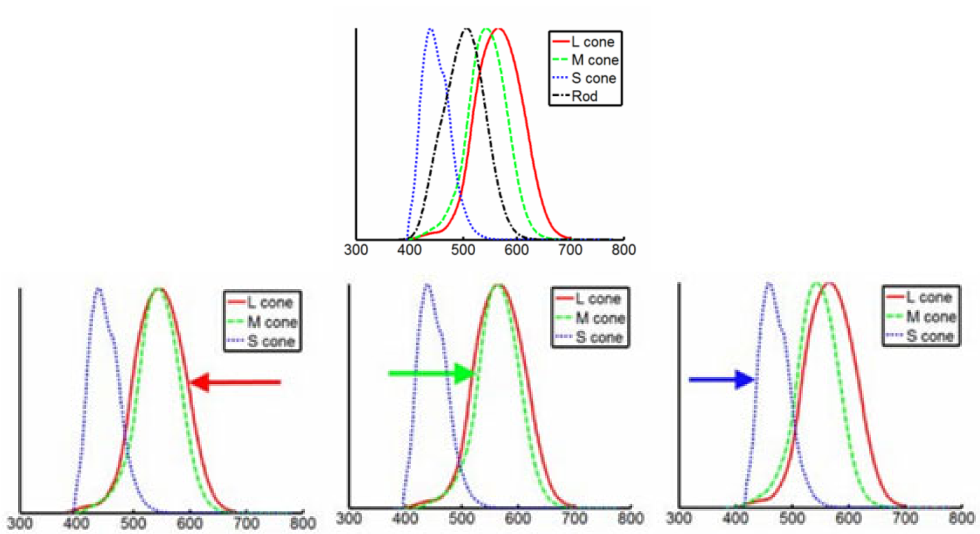

Figure 1. Spectral sensitivity of rods and the three cell types: Top, normal viewer; Bottom, from left: protanopes, deuteranopes, tritanopes. Images taken from [9]

Normal color perception requires that three types of photoreceptors are present in the eye and function correctly. These cells contain pigments sensitive to three portions of the visible spectrum, and are usually known as S cone cells (short wavelength, responsible for perceiving blue), M cone cells (medium wavelength, green), and L cone cells (long wavelength, red). Since an accurate reception of a color depends on all three pigments involved, variation in these pigments' composition – and therefore the cells' sensitivities – will manifest as a denaturation in an individual's vision.

Viewers that experience abnormalities in color vision can be classified as exhibiting *anomalous trichromacy* (all three color pigments are present, but one of them is anomalous), *dichromacy* (only two of the pigments are present), and *monochromacy* (a single pigment or none at all; the rarest of the three)[9]. In reference to the pigments, *protan* is used if the red pigment is affected, *deutan* for green, and *tritan* for blue. Thus, trichromats (persons exhibiting trichromacy) can be either *protanomalous*, *deuteranomalous*, or *tritanomalous*, while dichromats can be either *protanopic*, *deuteranopic*, or *tritanopic*.

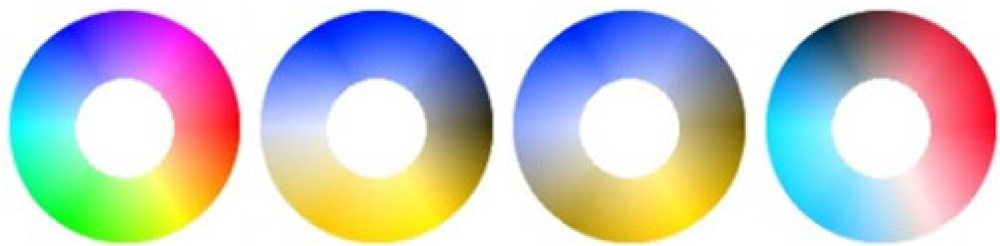

Figure 2. Simulated color perception: From left to right: normal spectrum, protanopes, deuteranopes, and tritanopes. Image taken from [9].

A simulation of color perception with the full spectrum as reference is presented in figure 2, while figure 3 provides an estimation of how a real image might be perceived by viewers with perception anomalies.

Figure 3. Simulated perception of a natural image: From left to right: normal viewers, protanopes, deuteranopes, and tritanopes. Image taken from [10]

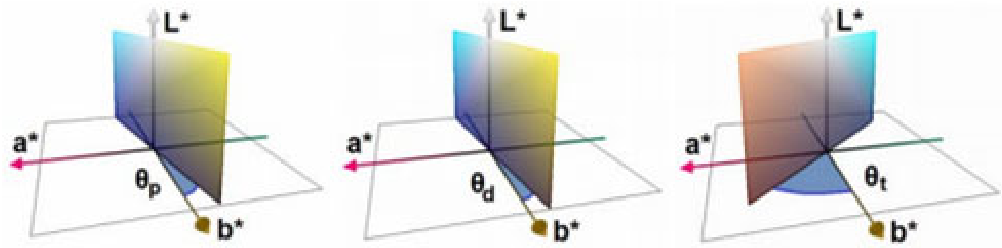

Figure 4. Dichromat color planes: From left, protanope ($\theta_p = -11.48°$), deuteranope ($\theta_d = -8.11°$), tritanope ($\theta_t = 46.37°$). Image taken from [9]

Making use of the CIE-L*a*b* standard, dichromat perception can be approximated[9] through a set of three planes defined within the color space. Each anomalous perception is expressed as a deviation between the L*b* plan and a plan rotated around the L* axis, with reference to the b* axis. For each of the three types of dichromat an angle has been determined by Kuhn et al.[11], as illustrated in figure 4.

RECOLORING METHODS

With regards to the different types of color vision deficiency, research in the field has been largely focused on dichromacy, and prevalently on *red–green* insensitivity and blindness, as these forms of deficiency are the most commonly occurring[1].

Rasche et al.[12][13] proposed an algorithm focused on transforming color images to grey scale images, and which can be extended to accommodate color blindness. While the results are very promising, this method can have a high computational cost, and does not always deliver a natural-seeming image.

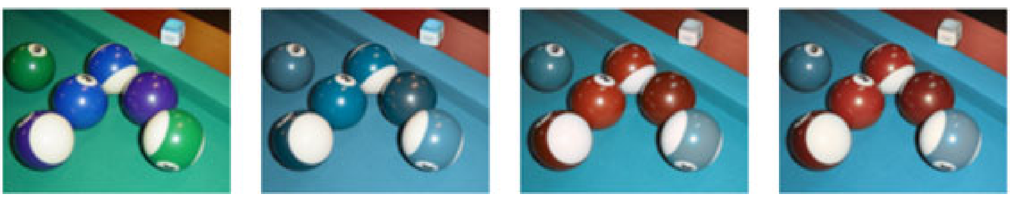

Figure 5. Rasche et al [12] proposed algorithm: From left to right: a natural image and the natural image as seen by a tritanope; a recolored image using the Rasche et al. algorithm and the recolored image as seen by a tritanope. Image taken from [12]

The paper defines an objective function, incorporating two main goals — preserving contrast and maintaining luminance consistency — and ultimately resolves to a linear optimisation problem. The proposed procedure can be expressed as follows:

```
apply quantization to select N colors / select reference
points
solve linear programming problem using reference points
apply interpolation using transformed reference points
```

The linear problem that is to be solved in this method is the minimization of the per-component error (between the ideal color values and the real values), with the goal of maintaining relative contrast differences between colors, by employing constrained multidimensional scaling technique. This type of algorithms do not scale well, wherefrom the importance of the quantization step, and the long run times reported by the authors.

One technique that aims to preserve the naturalness of images recolored for dichromat viewers is proposed by Kuhn et al.[11]. The algorithm is deterministic, hence its results should be consistent and reproducible.

Figure 6 Rasche et al.[12] and Kuhn et al.[11]: From left to right: a natural image and the natural image as seen by protanopes; a recolored image using Rasche et al. and a recolored image using Kuhn et al. Image taken from[11]

The proposed algorithm consists of a quantization step followed by a mass-spring system optimization step, and a final reconstruction step, as such:

```
apply quantization to select N colors / select reference
points
optimize mass-spring system
apply interpolation using transformed reference points
```

The mass-spring optimization allows both for a short computation time, and a more natural looking result, due to the fact that this method does not affect colors that are perceived the same by trichromats and dichromats.

A mass-spring model contains a number of particles, each with a mass and a position in space, connected to one another through springs with a certain rest length. Particles will naturally push and pull each other; based on the rest length of the spring that connects them, they move as much as their mass allows them (i.e. a heavy particle will move less than a lighter one). Eventually, a point will be reached where the particles have arranged themselves into an optimal configuration, which can be used as an optimization heuristic if a problem can be formulated to fit the model.

In this case, the particles are the quantized color reference points, and their mass is inversely proportional to how problematic they are for viewers with a certain deficiency, while the spring’s rest length is the perceptual difference between colors.

Another method that places great importance on naturalness is introduced by **Huang et al.** [14], who also leave the luminance component untouched, only manipulating the a* and b* components, and use a remapping heuristic that modifies colors proportionally to their relevance to the examined dichromacy. Results show improvement over the Rasche et al.[12] method, both in perceived contrast and naturalness.

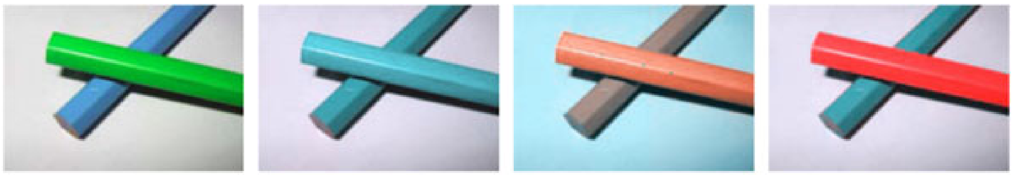

Figure 7 Rasche et al.[12] and Huang et al.[14]: From left to right: a natural image and the natural image as seen by a tritanope; a recolored image using Rasche et al. and a recolored image using Huang et al. Image taken from[14]

The driving principle behind this technique's optimization phase is a series of optimization steps, applied to each selected color in order, based on the perceived anomaly in deficient viewers and consisting of a minimization of deviation in the contrast between a pair of two original colors and a pair of corresponding remapped colors.

```
apply quantization to select N colors / select reference
points
prioritize reference points
for each reference point, starting with the highest priority,
     optimize transformed point using previously transformed
     points
apply interpolation using transformed reference points
```

Just like Kuhn et al. [11], clustering is employed in order to reduce the computational load, and interpolation to build the final result.

CONCLUSIONS

Given the importance of visual imagery, as well as its widespread use in digital media, methods of transforming images to suit color deficient viewers can be very valuable, and research in the field has shown potential.

The first method discussed in this paper, proposed by Rasche et al. [12] provides a good reference point and produces good results, but lacks first in efficiency, due to very high processing times, and, secondly, in naturalness. Images produced by Rasche et al. often do not preserve the perceived aesthetic of an image, focusing mainly on removing confusing color pairings. A more optimized implementation of the algorithm, in view of increasing computation speed, may prove useful.

Kuhn et al. [11] seek to improve both processing times and the naturalness of the result image. By using a mass-spring system in the optimization step, not only is the algorithm's speed superior to that of Rasche et al., but since certain colors, ones that do not affect a deficient viewer's perception, are not modified, the final product is noticeably more natural seeming.

Similarly, Huang et al.[14] also obtain an increase in naturalness, by prioritizing colors based on the effect they have on a dichromat individual's perception. The introduction of this processing order also reduces the computational load, with a single original color-transformed color pair being treated at a time.

Although very productive, studies so far concern static imagery. While these methods would provide good transformations for single frames, if applied sequentially, to each frame of a video, the end result may suffer from color changes. The non-uniformity introduced by the lack of inter-frame consistency may produce unpleasant results, or even further undermine an already anomalous perception. Machado and Oliveira[15] present a temporally coherent method for contrast enhancement, though their technique seems aimed at data visualization, thus has not focused on preserving naturalness.

Possible future work in this area of interest can focus on three aspects: optimizing performance of existing techniques, the scarceness of publicly available software applications that can perform color transformations for dichromats, as well as development of a procedure suitable for naturalness-preserving processing of video content.

As far as multi-frame content is concerned, using the existent single-frame methods as a starting point, a proposed algorithm might follow these steps:

```
for each frame in a video,
     apply color transformation
     build a look-up table using the recolored frame
for each color pair in the look-up tables,
     considering its values along frames, apply a smoothing
     filter
for each frame in a video,
     recolor using smoothed look-up table / interpolation
```

The above mentioned look-up tables are meant to provide an approximation of the recoloring of each frame, by cataloguing how each original color was transformed in each context. By smoothing the transformed values over time, a better overall consistency could be achieved, although the initial selection of reference points might prove problematic, particularly since skipping the quantization step would be very costly in terms of computational effort, especially considering that video formats are often high-resolution.

Another potential approach might be the batch-processing of frames, by selecting a set of frames, stitching them together to provide input for a single-frame transformation method, and separating the output to the original frames, although this relies heavily on the premise of a high-performance, time-efficient recoloring method, and would still cause inconsistency issues in videos with lengths larger than the algorithm's supported input size.

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REFERENCES

[1] W. R. Miles, "Color Blindness in Eleven Thousand Museum Visitors," Yale Journal of Biology and Medicine, vol. 16, no. 1, pp. 59–76, 1943.

[2] H. B. Kim, S. Y. Lee, J. K. Choe, J. H. Lee, and B. H. Ahn, "The incidence of congenital color deficiency among Koreans," Journal of Korean Medical Science, vol. 4, no. 3, pp. 117–120, 1989.

[3] J. Scanlon and J. Roberts, "Color Vision Deficiencies in Children, United States," Rockville, MD: National Center for Health Statistics, vol. 11, no. 118, pp. 1–34, 1972.

[4] J. Z. Xie et al., "Color vision deficiency in preschool children: the multi-ethnic pediatric eye disease study," Ophthalmology, vol. 121, no. 7, pp. 1469–74, Jul. 2014.

[5] R. S. Hunter, "Photoelectric Color Difference Meter," Journal of the Optical Society of America, vol. 48, no. 12, p. 985, 1958.

[6] B. Hill, T. Roger, and F. W. Vorhagen, "Comparative Analysis of the Quantization of Color Spaces on the Basis of the CIELAB Color-Difference Formula," ACM Transactions on Graphics, vol. 16, no. 2, pp. 109–154, 1997.

[7] K. M. M. Krishna Prasad, S. Raheem, P. Vijayalekshmi, and C. Kamala Sastri, "Basic aspects and applications of tristimulus colorimetry," Talanta, vol. 43, no. 8. pp. 1187–1206, 1996.

[8] A. Shams-Nateri, "Estimation of CIE tristimulus values under various illuminants," Color Research and Application, vol. 34, no. 2, pp. 100–107, 2009.

[9] G. M. Machado, "A model for simulation of color vision deficiency and a color contrast enhancement technique for dichromats," Universidade Federal do Rio Grande do Sul, 2010.

[10] L. T. Sharpe, A. Stockman, H. Jägle, and J. Nathans, "Opsin genes, cone photopigments, color vision, and color blindness," in Color Vision: From Genes to Perception, K. R. Gegenfurtner and L. T. Sharpe, Eds. Cambridge University Press, 2001, pp. 3–51.

[11] G. R. Kuhn, M. M. Oliveira, and L. A. F. Fernandes, "An Efficient Naturalness-Preserving Image-Recoloring Method for Dichromats," IEEE Transactions on Visualization and Computer Graphics, vol. 14, no. 6, pp. 1747–1754, 2008.

[12] K. Rasche, R. Geist, and J. Westall, "Re-coloring images for gamuts of lower dimension," Computer Graphics Forum, vol. 24, no. 3, pp. 423–432, 2005.

[13] K. Rasche, R. Geist, and J. Westall, "Detail preserving reproduction of color images for monochromats and dichromats," IEEE Computer Graphics and Applications, vol. 25, no. 3, pp. 22–30, 2005.

[14] C. R. Huang, K. C. Chiu, and C. S. Chen, "Key color priority based image recoloring for dichromats," Lecture Notes in Computer Science, vol. 6298, PART 2, pp. 637–647, 2010.

[15] G. M. Machado and M. M. Oliveira, "Real-time temporal-coherent color contrast enhancement for dichromats," Computer Graphics Forum, vol. 29, no. 3, pp. 933–942, 2010.