A Skillet-Based Recoloring Algorithm for Dichromats

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***Abstract*—The color is a valuable communication resource, not just as part of the message itself, but also as a way of discriminating between the diverse contents of a given message. However, not all people have the ability to distinguish the color in a normal way. About 5% of the world population (8% of men) has a visual impairment, called color vision deficiency (CVD) or, simply, colorblindness. This vision deficiency also has a negative impact in both virtual and real worlds, because it compromises the correct interpretation of the contents across different media and envrironments. This issue is critical because of the increasing availability of multimedia contents in many places, particularly over the web. This article proposes a novel algorithm to adjust the colors for dichromate people (deuteranopes and protanopes), in particular for still images found over the web via browsers that take advantage of HTML5 markup language for graphics.**

***Keywords*—Color blindness, dichromacy, CVD people, recoloring algoritms.**

I. Introduction

The correct perception of the color by human beings is crucial for the their awareness of the surrounding world and their interactions with other individuals, independently of the communication media used in the daily life. Color helps us to understand the message and the surrounding world.

However, a significant part of people (5% of the population) do not have a normal perception of color because they suffer from a visual impairment called color vision deficiency (CVD), sometimes called colorblindness. This visual condition distorts or limits the color gamut visualized by impaired people, so compromising the integral understanding of the message contents (e.g. reading a colored text written over a different colored background may be an impossible task for those people because of the lack of enough contrast).

The awareness of this problem has led a number of researchers to develop efforts to overcome such a problem, as it is the case of recoloring algorithms. Recall that the color essentially is a 3D entity. In fact, the human eye perceives color as a combination of the three primary color: red, green and blue. Those individuals with normal vision or without color anomalies are known as *trichromats*. However, CVD people cannot see the color in a normal way, mainly due to hereditary problems that affect the cell cones. Depending on the degree of the impairment [1],we can list the following CVDs: *anomalous trichromacy*, *dichromacy* and *monochromacy*.

Anomalous trichromats see colors as normal people but with distortion. This distortion occurs because one sort of retina cones (at least) does not work properly [20] [17]. Depending on the sort of cones affected, the anomalous trichromacy has distinct designations: protanomaly (also known as red-weak vision), when the L-cones are affected, deuteranomaly (green-weak vision) and tritanomaly (blue-weak vision) when the anomaly is related with the M-cones and S-cones, respectively [25].

Dichromats are those people with a damaged color channel, so that one sort of cones does not work indeed, what is as if a sort of cones did not exist on retina. The color perception is thus reduced to two channels (i.e., a 2D domain). Depending on the type of inoperative cones, we have the following dichromacy anomalies: protanopy, deuteranopy and tritanomaly, which are the designations for the absence of the L-cones, M-cones and S-cones, respectively.

Monochromacy is even more severe than the previous vision anomalies because only one sort of cones works properly, that is, the color domain of monochromats is 1D. This corresponds to the gray scale vision, but some of these people see grays with a touch of blue.

This paper describes a simpler and more efficient recoloring algorithm than many those found in the literature, because it uses a more intuitive color model —more specifically, the HSV model— and because every single pixel is only processed once. This means that the complexity of the algorithm is $\mathcal{O}(n)$. Nevertheless, this algorithm only applies to dichromats (in particular, deuteranopes and protanopes).

The paper is organized as follows. Section II approaches the color models, in particular those used in the design and implementation of our algorithm. Section III reviews other works related to recoloring algorithms. Section IV describes our algorithm. Section V presents relevant experimental results produced by our algorithm, including a comparative analysis with other two recoloring algorithms extant in the literature. In the end of the paper, we draw some important conclusions about our recoloring algorithm.

II. Color Models

Recoloring algorithms follow different strategies to remap the color to the visible spectrum of each CVD person, taking advantage of the properties of extant color spaces and models. So, let us review those color models that have been more relevant in the design and implementation of our algorithm.

A. RGB

Most displaying devices use the RGB color model. The primary colors are the red, the green and the blue. Any other color results from combining these three colors, that is, a given color is represented by the triplet (R, G, B), where $0 \leq R, G, B \leq 255$. Varying these three values in

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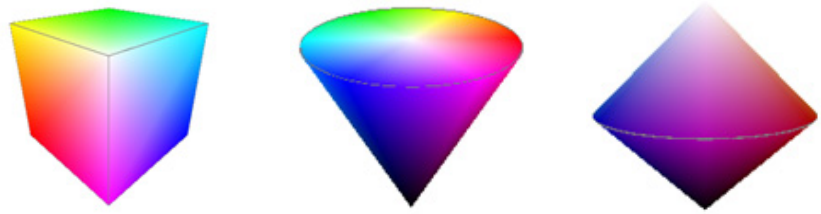


(a) (b) (c)

Fig. 1. Color spaces: (a) RGB; (b) HSV; (c) HSL.

their complete domain, one gets a color cube, which is the geometrical representation of the RGB color space (Fig. 1(a)). We get the black when $(R, G, B) = (0, 0, 0)$ and the white when $(R, G, B) = (255, 255, 255)$, so that the color gets lighter when the primaries increase their values.

However, the RGB model is somewhat unintuitive in the way we achieve or change colors. For example, it is not obvious how to get a dark yellow or, alternatively, a lighter magenta. These difficulties motivated the appearance of some other color spaces [10], in particular those that are close to human perception, namely: HSL (hue, saturation, luminosity), HSV (hue, saturation, value) and the HSI (hue, saturation, intensity). These more intuitive color spaces are sometimes called ”phenomenal color spaces“ [27], which evolved from the Munsell Color System [18].

B. HSV

As any other phenomenal color space, we obtain HSV by means of a linear transformation of the RGB color space, having the advantage of allowing us to specify different colors in a very intuitive manner [4]. Hues have to do with pure colors, the most saturated colors. We get a more (resp., less) vivid color by increasing (resp., decreasing) the saturation of a hue. The third parameter, named value, has to do with the grayscale; for example, by changing the value of a red hue we get either a lighter red or a darker red.

Therefore, the HSV colors are expressed in triplets (H, S, V), where $0^o \leq H < 360^o$, $0 \leq S \leq 1$ and $0 \leq V \leq 1$. In geometric terms, the HSV color model is a cone (Fig. 1(b)). For a fixed hue on the border of the cone, the saturation increases from the cone axis to the border of the cone, where it reaches the maximum value. The axis of the cone works as a gray scale (value parameter), so that the darker color (black) is located at the apex of the cone, while the lighter color (white) is at the center of the cone base. In the related literature, the value is sometimes designated brightness, so the color space sometimes is referred as HSB instead of HSV [26] [28].

C. HSL

This color space is similar to the previous HSV color space because the colors are also expressed in triplets (H, S, L), where $0^o \leq H < 360^o$, $0 \leq S \leq 1$ and $0 \leq L \leq 1$. But, now the maximum of chromaticity is achieved at the midpoint of the grayscale $L = 1/2$, not at the maximum value of luminosity $L = 1$. This implies that the geometry of the HSL color space is a double cone with a common base, so that the white color is located at the top apex while the black color is at the bottom apex (Fig. 1(c)).

There exists another color space, called HSI, whose geometry is the same as that one of the HSL color space [5], but the linear transformations that allow us to obtain HSL and HSI colors from RGB have different formulations.

III. Related Work

In the literature, we find recoloring algorithms for still images and also for video [13] [15] [6] [9], although those for still images are predominant. The need for recoloring images comes from the fact that people with some degree of CVD may be not capable of distinguishing colors of adjacent regions of an image, what leads to misunderstanding and confusion about the image itself. This means that the recoloring serves the purpose of contrasting the color elements of an image in order to allow an individual to get a better perception and understanding about such an image.

The recoloring algorithms for anomalous trichromats essentially are corrective algorithms of the color distortion, since these people tend to see almost all colors of the visible spectrum, yet in a distorted way [16] [21].

In respect to dichromats, the recoloring algorithms replace some colors by others because these people have no ability to see certain colors, looking for thus the contrast between the colors of the several elements in an image [30] [19] [22] [7] [14] [11] [29] [24] [9] [3].

Monochromats are rare in people with CVD, so that algorithms are inexistent in practice. As much as we know, the exception are the works due to Rasche et al. [23] [22] and Lai and Chang [12], who introduced automatic recoloring techniques for dichromats and monochromats. However, for monochromats, the algorithms related with the color-to-grayscale conversion can be applied as well.

IV. The Algorithm

The algorithm proposed in this paper has been designed for dichromats, in particular for deuteranopes and protanopes. The third subcategory of dichomats, known as tritanopes, is not considered in this paper because they require a slightly different recoloring procedure. Moreover, deuteranopy and protanopy are the most common CVD in dichromats.

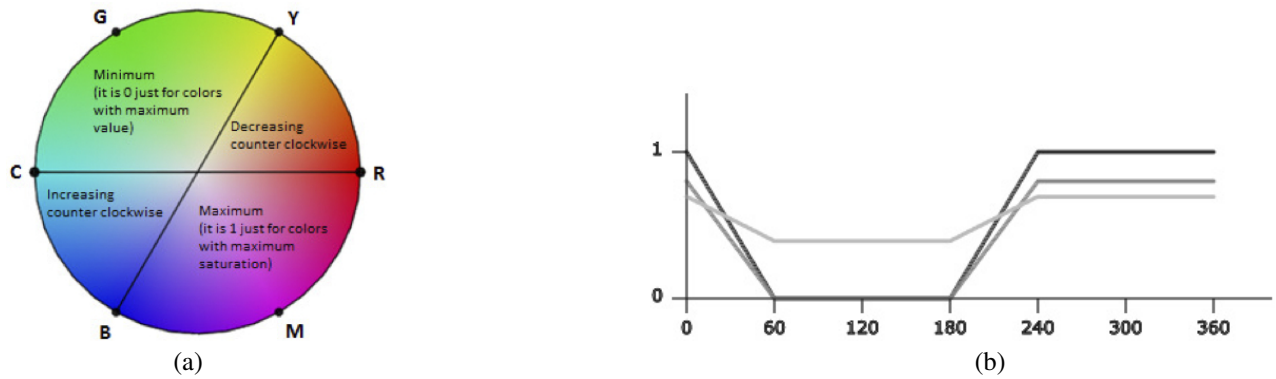


Fig. 2. (a) Behavior of the magenta function μ in the HSV wheel (cone base) for $V = V_{MAX}$; (b) three graphs of μ for different values of S and V.

A. Recoloring Function

Our algorithm uses the HSV color space and has the purpose of replacing colors like pink, red and orange, which are normally confused with greens, by other colors. So, after converting the color of each pixel from (R, G, B) to (H, S, V), we have to re-map the hues prone to confusion, which corresponds to the following trivariate recoloring function:

$$H' = H + \Delta H, \quad S' = S, \quad V' = V \tag{1}$$

where the hue variation ΔH is as follows:

$$\Delta H = \begin{cases} 0 & \text{if } H \in \mathbf{I} \\ \sigma(r, g, b) & \text{if } H \notin \mathbf{I} \end{cases} \tag{2}$$

with $\mathbf{I} \approx [60^{\text{o}}, 280^{\text{o}}]$ denoting the region of greens and blues.

Note that deuteranopes see blues as normal people; hence $\Delta H = 0$ for hues in the range of blues (cf. (2)). Deuteranopes also see greens and yellows reasonably well, so their blindness is in relation to reds and other colors having a significant percentage of red like pinks, oranges and magentas. Thus, the recoloring problem reduces to find ΔH for confusing colors (i.e., $H \notin \mathbf{I}$). For that, we use the hue remapping function:

$$\sigma(r, g, b) = (H - 130) \,.\mu(r, g, b) \tag{3}$$

where μ is the magenta function $\mu(r, g, b) = 1 - \frac{g}{255}$ introduced in Yang and Ro [30], but where (r, g, b) is not the original color (R, G, B) of the pixel; instead, it is the color obtained after converting (H, S_{MAX}, V_{MAX}) to (r, g, b).

B. Hue Remapping Function

Looking at the HSV color wheel in Fig. 2(a), we see that green and magenta are opposite colors, that is, the pure green has no percentage of magenta, and the pure magenta no percentage of green, that is, green is inversely proportional to magenta. Because the leading idea of our algorithm is to remap colors with significant percentage of magenta (the confusing colors) to other colors, we use the magenta function $\mu(r, g, b)$ as an important factor of the hue remapping function $\sigma(r, g, b)$.

Fig. 2(b) shows the graphical representation of the original magenta function $\mu(R, G, B)$ for three different values of saturation and brightness. In these circumstances, the recoloring depends on the saturation S and the value V. Consequently, two colors with the same hue do not necessarily map into the same hue. This problem inherent to the formulation of (Yang and Ro, 2003) has been solved by our algorithm by maximizing the saturation and brightness as expressed in (3), what corresponds to the darker gray skillet line in Fig. 2(b). In this way, the hue remapping of colors is invariant to saturation and brightness (or value) parameters.

Note that the magenta function takes on its maximum value 1 on magenta region (with no green), what corresponds to the perimeter of the color wheel between 240° (B) and 360° (R). Conversely, the magenta function takes on its minimum value 0 on green region (with no magenta) between 60° (Y) and 180° (C). In the other two regions, the magenta function decreases linearly from its maximum to its minimum and vice-versa.

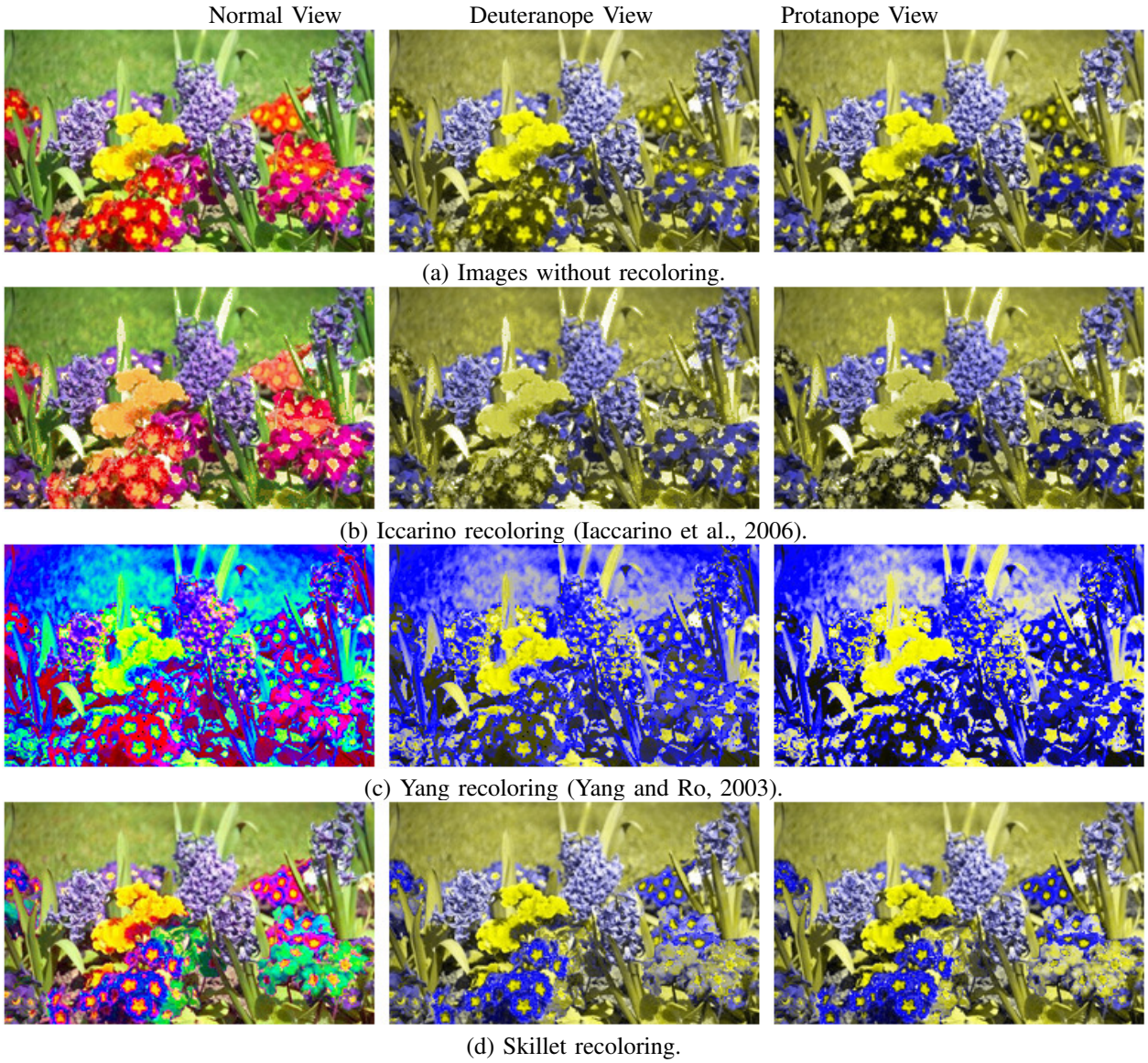
Therefore, the magenta function μ is 0 when $H \in [60^{\text{o}}, 180^{\text{o}}]$ and, consequently, $\Delta H = 0$ so that the greens stay unchanged and yellows and cyans stay also almost unchanged. When the value of hue is less than 130°, the ΔH becomes negative in the interval $[0^{\text{o}}, 60^{\text{o}}]$ of the domain of the magenta function μ, so the reds of the first quadrant are pulled into the fourth quadrant towards to violet/blue. On the other hand, when the value of hue is greater than 130°, the ΔH becomes positive, so the reds and magentas of the fourth quadrant are pulled into the third quadrant towards to violet/blue. In this way, we are able to remap hues of the critical area (of oranges, reds and pinks) onto other hues outside the green area.

V. Experimental Results

All experiments and testing were carried out on an Intel Quad Core CPU Q9550 with 4G RAM and a 64-bit Windows operating system. Our algorithm was implemented in JavaScript in order to run the corresponding program on an HTML5 web browser because we have the goal of automatically adapting web browsers for CVD people. In particular, we intend to design and implement a recoloring algorithm for deuteranopes and protanopes, mainly because they are the most frequent cases of dichromacy and also because they see the colors in a similar manner. Also, we have focused testing on still images, not video.

We compared our algorithm to those due to Iaccarino et al. [8] and Yang and Ro [30] for the following reasons:

- They also cover the universe of deuteranopes and protanopes.
- They also sustain on phenomenal color spaces (i.e., HSV, HSL or HSI).



(a) Images without recoloring.

(b) Iccarino recoloring (Iaccarino et al., 2006).

(c) Yang recoloring (Yang and Ro, 2003).

(d) Skillet recoloring.

Fig. 3. Recoloring for thricromats (without CVD) (left), deuteranopes (center) and protanopes (right).

A. Time Performance

Besides, to make sure about the time performance of three algorithms, they were all implemented and ran using the same setup aforementioned. Table I shows the average timing results for these algorithms, having been considered a dataset of about one thousand of 250×180 and 580×434 images. As shown, our algorithm gets 25% faster than Yang-Ro algorithm and 15% to 25% when compared to the algorithm due to Iaccarino and colleagues. This is so because these two competitor algorithms need a pre-processing step to get the 'maximum hue variation' and 'maximum saturation variation' of each image, in the case of Iaccarino et al. algorithm, and to get the values of 'greenPixels' and 'redPixels' in the case of Iaccarino and colleagues.

B. Comparative Recoloring

To compare those three algorithms, we had to find the way of simulating how deuteranopes and protanopes see colors in images. For this purpose we used the simulation algorithms proposed Brettel et al. [2]. We also chose images with high chromatic diversity as that one depicted in Fig. 3.

TABLE I. AVERAGE TIME SPENT BY THE ALGORITHMS IN RECOLORING 250×180 AND 580×434 IMAGES.

	250×180 images	580×434 images
(Iaccarino et al., 2006)	0.136 seconds	0.575 seconds
(Yang and Ro, 2003)	0.149 seconds	0.614 seconds
Skillet recoloring algorithm	0.110 seconds	0.508 seconds

As shown in Fig. 3(a), deuteranopes ant protanopes correctly see yellows and blues, so these vivid colors are the only ones that remain unchanged, beyond the dingy colors. The reds and pinks are mapped into smug greens and blues, both seen as smug blues, but in a different manner. In respect to greens, deuteranopes and protanopes see them with less saturation and lower brightness, that is, greens are seen as faint greens. It is also clear that these CVD people are not able to see pinks, reds and oranges, which are mistaken by greens with more or

less saturation and brightness.

Fig. 3(b) shows the recolored images that result from the algorithm due to Iaccarino et al. [8]. We observe that the resulting images lost chromatic diversity. Even worse is the fact that deuteranopes and protanopes can no longer see vivid yellows, which are colors they see correctly in practice. Thus, this recoloring technique does not bring a considerable enhancement in color perception from the point of view of deuteranopes and protanopes.

Fig. 3(c) depicts the resulting images produced by the algorithm of Yang and Ro [30]. Unlike Iaccarino et al. [8], the algorithm proposed by Yang and Ro [30] retains the vivid yellows, but the produced images are too bluish, what is unnatural and noisy, with a general loss of detail. Besides, the greens are largely mapped into blues, so that deuteranopes and protanopes can no longer see greens in practice, resulting in a less chromatic perception.

In respect to our algorithm, whose visual results are shown in Fig. 3(d), we note that deuteranopes and protanopes continue to be able to see yellows, blues and greens, being the confusing colors remapped to a more enlarged zone that excludes greens of the HSV color wheel. Besides, the image continues to have a clean look, after the recoloring process.

VI. Conclusions

In the real world, it is much more important to be able to distinguish between reds and greens than between any other colors, as needed to, for example, correctly interpret the transit signage. With this in mind, we have designed a recoloring algorithm that eliminates the confusion between reds and greens. To achieve that, the algorithm remaps the red region to a more enlarged region that does not include the greens, using the maximum saturation S_{MAX} and maximum value V_{MAX} in order to guarantee that any two different hues are mapped into two distinct hues.

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