Intelligent modification for the daltonization process of digitized paintings

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Abstract. Daltonization is a procedure for adapting colors in an image or a sequence of images for improving the color perception by a color-deficient viewer. In this paper an intelligent/enhanced daltonization method for individuals suffering from protanopia is proposed. The algorithm implements logical image masking in order to modify the colors that are confused and to preserve those colors that are perceived correctly. The proposed method modifies iteratively the parameters for image daltonization after the provision of the initial conditions. The distinctive characteristic of the proposed approach is that when it is combined with a color-checking module, optimum daltonization parameters are effectively identified. Examples are provided in details, as well as screenshots from the algorithm when it is applied in digitized paintings/artworks.

1 Introduction

The human color vision is derived from the response of three cones (or photoreceptors) contained in the retina of the eye. Normal color vision is trichromatic. It is initiated by the absorption of photons in three classes of cones, whose peak sensitivities lie in three regions of the spectrum, the long-wavelength (L), middle-wavelength (M) and short-wavelength namely.

Modification of one of three classes of cone pigments invokes Color Vision Deficiency (CVD). There are three kinds of CVD. The first is called dichromacy, while the most common is called anomalous trichromacy. There is also an extreme case, called achromatopsia. In this study, only dichromacy is addressed.

Studying deeper the deficiency of dichromacy, it is found that there are three types of dichromacy: protanopia, deuteranopia and tritanopia. All colors visible for trichromacy (normal vision) are shown as two monochromatic hues. In protanopia the spectrum is seen in tones of yellow and blue and in deuteranopia there confusion of red and green. Relatively rare is the tritanopia, where the spectrum is seen in tones of red and green.

Many researchers have conducted research for appropriately modeling the visually impaired vision for dichromacy, presenting algorithms to simulate what individuals

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with vision deficiency see. In [1], a model for daltonization technique is presented based on the work published in [2] in order to modify a digital image so that it is more visible to people with CVD. The former work is also compared to the online results that are obtained visiting the Vischeck site [3].

The problem of color adaptation according to user's perception is also addressed in [4], [5]. In [4] paper, among other issues, the problem of tailoring visual content within the MPEG-21 Digital Item Adaptation (DIA) framework to meet users' visual perception characteristics was addressed. The image retrieval aspect for people with CVD was discussed in [6]. Even a physiologically motivated human color visual system model which represents visual information with one brightness component and two chromatic components was proposed for testing the color perception of people suffering from CVD [7].

2 Simulating protanopia with image processing

The three types of dichromacy are simulated by converting the "normal" RGB color space into its dichromatic versions using the commonly accepted algorithms developed in [2], [8]. In this session, only the matrices for simulating protanopia are presented, since the focus of this study is for protanopia. It should be emphasized however, that as the simulation contains the color information in RGB values that are often of unknown phosphor chromaticity, we accept the fact that an error may be inserted in the calculations.

The method is based on the LMS system, which specifies colours in terms of the relative excitations of the longwave sensitive (L), the middlewave sensitive (M), and the shortwave sensitive (S) cones. As dichromats lack one class of cone photopigment, they confuse colours that differ only in the excitation of the missing class of photopigment. In contrast to the case of the trichromatic observer, who requires colour specifications by three components, two components are sufficient to specify colour for the dichromat. Thus, a rule may be constructed to reduce any set of confused colours to a single three-component colour specification.

As in [1], the transformation algorithm presented in [1] for the color deficient simulation is adopted. This involves a transformation from RGB to LMS color. This procedure is achieved by a matrix multiplication, which is described in equation (1).

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 17.8824 & 43.5161 & 4.1193 \\ 3.4557 & 27.1554 & 3.8671 \\ 0.02996 & 0.18431 & 1.4670 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

According to [2], the above transformation results should be applied in the following linear transformations for reducing the normal colour domain to the protanope colour domain as indicated in equation (2).

$$\begin{bmatrix} L_p \\ M_p \\ S_p \end{bmatrix} = \begin{bmatrix} 0 & 2.02344 & -2.52581 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (2)$$

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$$\begin{bmatrix} R_p \\ G_p \\ B_p \end{bmatrix} = \begin{bmatrix} 0.0809 & -0.1305 & 0.1167 \\ -0.0102 & 0.0540 & -0.1136 \\ -0.0003 & -0.0041 & 0.6935 \end{bmatrix} \begin{bmatrix} L_p \\ M_p \\ S_p \end{bmatrix} \quad (3)$$

Transformation of $L_pM_pS_p$ to $R_pG_pB_p$ is obtained using the inverse matrix of equation (1) having of course obtained the respective values from equation (2). According to [2] the appropriate table is shown in equation (3) above. A simulation of the colors perceived by a protanope (a person suffering from protanopia) is highlighted in figure 1. It is evident that reddish tones are confused with black and moreover if those shades are neighbouring they are perceived as one color.

(a)

(b)

Fig. 1. (a) Original artwork ("Prism", modern abstract painting in acrylics by Bruce Gray [9]), (b) Simulation of the artwork as perceived by a protanope. Note the confusion of red and black areas in the artwork. www.brucegray.com/images/prism.jpg

3 Image daltonization

Daltonization is a procedure for adapting colors in an image or a sequence of images for improving the color perception by a color-deficient viewer. In this paper an enhanced image daltonization method is proposed, incorporating on the one hand the RGB to LMS transformation matrices described in [2]. On the other hand, we adopt the basic idea behind daltonization that is proposed in [1], which calculates an error matrix produced from the subtraction of the simulated $R_pG_pB_p$ values from the original image RGB. This error matrix exposes the color information that cannot be perceived by a protanope.
Initially, the error matrix E for the R,G,B channels is calculated, which is the subtraction of the respective channels in the image perceived by a protanope from the original's one. Therefore, the error E(r) in red channel is estimated using the formula $E(r) = R_n - R_p$, where n and p is the index for normal and protanope vision respectively. Similarly, the errors in the other two channels are $E(g)=G_n-G_p$ and $E(b)=B_n-B_p$. The process of adding the error values e(r,g,b) in the original image is demonstrated in figure 2a. This image could be considered as a daltonized version of the original image. Figure 2b presents how a protanope receives figure 2a.

(a) (b) (c) (d)

Fig. 2. (a) Daltonized with E, (b) protenope's perception of (a), (c) daltonized with E_{mod}, (d) protenope's perception of (c)

However, according to the method proposed in [1], the information of the error matrix (red values) is redistributed to the blue side of the spectrum, which is visible by a protanope. When this information is added on the original picture, a daltonized version of higher quality is created and the visibility of the new image is increased for a protanope.

Having calculated the error matrix E for every channel, research in [1] inserts a new matrix for the modification of the error. Specifically, on the one hand they propose that the error value E(r) should not be taken under consideration, while on the other hand red values in the pixel should contribute to the modification of green and blue values. In the matlab code that is available in the Web [1], the following 3x3 matrix is used for error modification.

$$M = \begin{bmatrix} m_1 & m_2 & m_3 \\ m_4 & m_5 & m_6 \\ m_7 & m_8 & m_9 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0.7 & 1 & 0 \\ 0.7 & 0 & 1 \end{bmatrix} \quad (4)$$

The matrix m when multiplied with the error matrix E provides the modified error matrix E_{mod}, which is then added to the original image in order to create the respective daltonized version. A similar method is proposed in [3], without the description of the algorithm details, though.

Using the above methods, very good results may be achieved in the majority of color images as shown in figure 2c and 2d. However, there is still a lot of space for improvements. The most obvious one is the fact that the adaptation parameters are manually chosen by the user until the resulting image is in adequate quality. In addition, there is always the possibility of color matching in areas of the image, before and after the daltonization technique. For these important reasons, an intelligent daltonization method is proposed in this paper, which is based on the previous studies, offering important solutions, though. More specifically, an automatic iteration technique is suggested for the selection of the adaptation parameters. Our selection, in addition, takes into consideration a color checking module, which eliminates the possibility of color matching between the original and the daltonized image.

It has to be noted here that the E_{mod}, which is added in the original image, is critical for the appearance of the daltonized image. Therefore the values of elements *m* in matrix M are decisive parameters for image daltonization. Actually they are the parameters identified in [1] as those ones that can be further modified according to the color content of the original picture. This is exactly one of the contributions of our work, as the selection of the

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m values is not a trial and error process. On the contrary, those values are selected in an iterative way as described in section 5.

Finally, among the issues that remain to be improved in image daltonization, is the problem of unnatural appearance after the image processing. In order to tackle with this problem, we suggest that the parameters m in matrix M should comply with the following rule:

$$\sum_{i=1}^{9} m_i = 3$$

If the above rule is satisfied, then it can be verified that, while the information of the error E_{mod} is redistributed to the visible spectrum side for a protanope, the energy of E_{mod} is not different from the energy of E. For instance, suppose that modifying some elements in matrix M, the energy of E_{mod} is greater that the energy of E. Adding that matrix to the original image for the daltonization, an individual suffering from protanopia will observe a more colourful image of higher energy. This effect will probably raise complaints for irregular appearance when the daltonized image is demonstrated to people with DCV.

Moreover, in the algorithm proposed in this paper, the matrix E_{mod} is always initiated with the following values:

$$M = \begin{bmatrix} m_1 & m_2 & m_3 \\ m_4 & m_5 & m_6 \\ m_7 & m_8 & m_9 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} \quad (5)$$

Note that the sum of the entries in the above matrix is equal to 3. Another difference of our approach compared to the one proposed in [1] is that m_1=-1 always. This way, the error in the red component is subtracted from the original image and redistributed to the other two channels according the content of the image following the procedure described in section 5.

4 RGB similarity checking

The RGB similarity checking module is a routine, which actually checks the existence of similar RGB values when a RGB value is given. The size of the neighbourhood is defined by the user and characterizes the degree of color resemblance.

Let as consider a colour C_1 with RGB colour co-ordinates (R_1, G_1, B_1) respectively. A cube cluster, centred in C_1, can be created having edge equal to d. Defining the edge d, cubic clusters may be created representing colour groups of similar appearance. Small values for d denote small clusters and thus small color tolerance. On the other hand, as the edge become greater the color tolerance for the cube increases.

1 **load** image I with size nxm
initialize List={}   //Empty list
read the reference value ref=(r_{ref},g_{ref},b_{ref}),
2 **for** i=1:n //n is x-size of image {
for j=1:m //m is y-size of image {
if I(i,j)={r_s,g_s,b_s}, where:$r_{res}-k \le r_s \le r_{res}+k$, $g_{res}-k \le g_s \le g_{res}+k$, $b_{res}-k \le b_s \le b_{res}+k$
then add the coordinates of (i,j) in List
return RGB_result=1; }}

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3 **if** List={Ø} then **return** RGB_result=0;
4 **else store** List for later processing

Any color (triplet of RGB values) lying out of the cube is considered just noticeably different, as compared to the color corresponding to the centre of that cube. For example, if colour $C_2(100,150,130)$ is considered and d=21, all the color combinations of C(100±10,150±10,130±10) will belong to the same cluster and they are not considerably different from C_2. For our experiments, d=21. An odd number was selected for d to achieve uniformity in x, y and z axis. The visual representation of the cube is illustrated in figure 3.

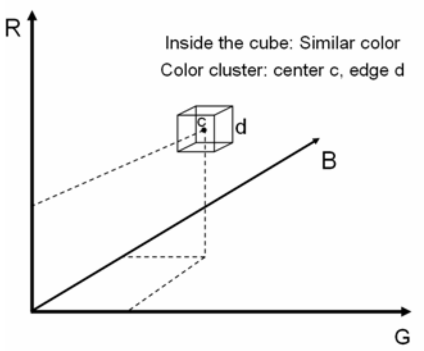

Fig. 3. Visual representation of the cube clusters.

5 Selecting the daltonization parameters

According to the methods [1],[4], the linear color transformation is performed in the whole image. As a result, colors that are not perceived erroneously by a person suffering from protanopia are also modified. This modification is usually small, but it is not insignificant. To tackle with this issue, the proposed method implements logical image masking in order not to alter the RGB values that are correctly perceived by a protanope. This is achieved, since image masking is subjected to the reference image only.
In addition, the proposed method calculates iteratively the parameters for image daltonization after the provision of the initial conditions. The distinctive characteristic of the proposed approach is that when combined with the RGB similarity checking module, the optimum daltonization parameters are iteratively selected.
An example of the proposed method is demonstrated in the following paragraphs,. Suppose that the initial image I_1 (figure 4a) is subjected to the algorithm. The RGB values for the vector image that is illustrated in figure 4a are A(255,51,204), B(73,73, 203) and C(193, 193, 255).

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Initially, the simulator is executed and image I_2 is created, which is the color image as perceived by a protanope (figure 4b). It is obvious that the left "1' is not visible for a protanope, as the respective RGB color for the background is now (73,73,203).

At this point, the error image E is calculated by simply finding the absolute value of the difference between I_2 and the original image I_1 that represent normal vision. Having defined the error image, the algorithm continues with image binarization with a very low threshold (e.g., 1%) in order to create a binary image mask I_{AND}. The image I_{AND} defines the parts of the image that should be daltonized. Fig. 4c denotes the binary mask I_{AND} for the example. This mask contains ones (white) in the part of the image that daltonization is necessary and zeros (black) in the remaining parts where there is no error and therefore daltonization is unnecessary. Then, by simple logical AND operation, image I_3 is calculated, which is the image to be daltonized. Moreover, $I_{correct}$ is the complement image of I_3, whose parts represents the colors of the initial image that are perceived correctly. $I_{correct}$ (see figure 4d) is the product of bitwise ANDing masking between the original image I_1 and the inverse I_{AND}.

If I_3 is initially subjected to the process of daltonization with matrix M, (see equation 5), then image I_4 is produced (Fig. 5a). In I_4 the background color has now the color D(73,209,255). It has to be noted that the background color is changed since the background color in the original image (A) is confused with color (B) in a protanope's case. However, if the protanope simulation module is executed again with I_4 producing image I_5 (see figure 5b), the color D(73,209,255) will be visualized as (193,193,255), which actually represents color C.

At this point, the RGB similarity checking module (with d=21), examines if color (193,193,254) is noticeably different from the colors that appear in image $I_{correct}$. In our example this color belongs to those colors that appear in $I_{correct}$ and therefore this implies that the error modification matrix M should change. If this step is omitted, then after the logical union of $I_{correct}$ and I_5, a protanope will not perceive at all the right "1", since it will have the same color with the background (see figure 5c).

The above example so far, exposes the necessity of continuous color checking during the daltonization process. The proposed algorithm continues the daltonization process checking for the existence of similar shades and modifying the error modification matrix is necessary.

In the second cycle (iteration) of the algorithm,the error modification matrix M is adapted obeying the following rule. The parameter m_4 in M is decreased at a defined step (i.e., 0.5), whilst parameter m_5 is increased equally in amount. This way, the distribution of red color in the blue channel is increased and in addition the same proportion of the green channel is also transferred to the blue one. Consequently, the matrix M_2 (the index refers to the iteration) is:

$$M_2 = \begin{bmatrix} m_1 & m_2 & m_3 \\ m_{4,1} & m_5 & m_6 \\ m_{7,1} & m_8 & m_9 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0.95 & 1 & 0 \\ 1.05 & 0 & 1 \end{bmatrix}$$

The daltonization of I_4 implementing M_2 will transform the color background color A(255,51,204) to a new color (73,200,255), which a person with protanopia will see as (185,185,254) as the protanopia simulator indicates. The latter color is again checked to ensure that is significantly different from all the colors that belong to

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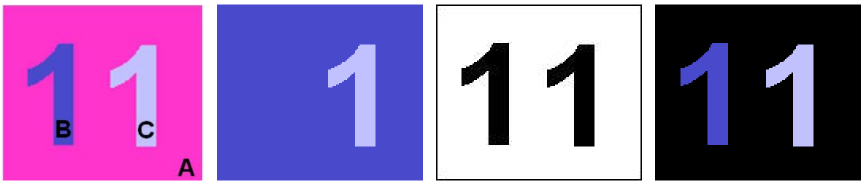
$I_{correct}$. However, once more this shade (185,185,254) is not noticeable different from color C(193, 193, 255). Remember that according to the RGB similarity checking module, if colour C_2(r,g,b) is considered and d=21, all the color combinations of C(r±10,g±10,b±10) belong to the same cluster and are not considerably different from C. The results of the second iteration are depicted in figure 6. Therefore, matrix M_1 is readapted and now (in the third iteration) takes the following values:

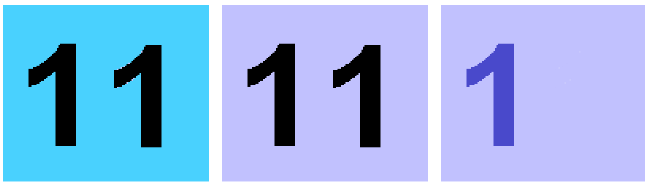
$$M_3 = \begin{bmatrix} m_1 & m_2 & m_3 \\ m_{4,2} & m_5 & m_6 \\ m_{7,2} & m_8 & m_9 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0.9 & 1 & 0 \\ 1.1 & 0 & 1 \end{bmatrix}$$

The daltonization of I_4 implementing M_3 will now transform the color background color A(255,51,204) to (73,191,255), which a person with protanopia will receive as (177,177,254). Fortunately, this color is significantly different from any other color values in $I_{correct}$ and after the logical union of I_5 with $I_{correct}$ the algorithm is terminated, producing image I_{final}. The results are shown in figure 7.



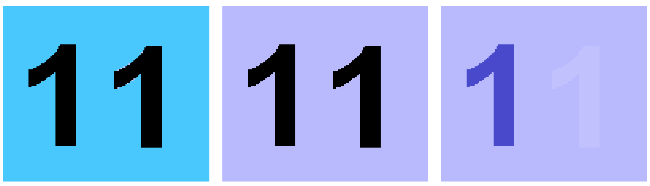
(a) (b) (c) (d)

Fig. 4 a. Original image, where A(255,51,204), B(73,73, 203) and C(193, 193, 255), b. protanope vision, c. image I_{AND}, d. image $I_{correct}$



(a) (b) (c)

Fig. 5. First iteration: a. image I_4, background color is D(73,209,255), b. protanope vision of I_4, background color is (193,193,254), c. product of union of I_4 and $I_{correct}$ (note that the right "1" is invisible by a protanope).



(a) (b) (c)

Fig. 6. Second iteration: a. image I_4, background color is (73,200,255), b. protanope vision of I_4, background color is (185,185,254), c. product of union of I_4 and $I_{correct}$ (note that the right "1" is very slightly visible by a protanope).

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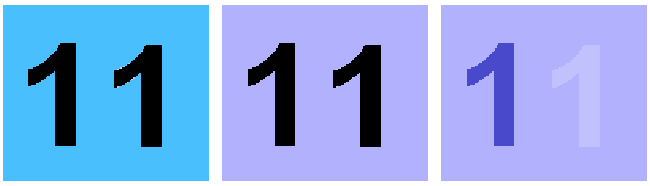

(a) (b) (c)

Fig. 7. Third iteration: a. image I_4, background color is (73,191,255), b. protanope vision of I_4, background color is (177,177,254), c. product of union of I_4 and $I_{correct}$ (note that the right “1” is now more visible by a protanope).

Fig. 8. Examples in two digitized paintings. First row: Vassily Kandinsky, improvisation7, second row: Paul Gaugin, marketday. First column: original artwork, second column: protanope vision, third column: protanope vision after the implementation of the proposed algorithm (for improvisation7 3 iterations were needed, for marketday 5 iterations were needed)

The pseudocode of the proposed algorithm can be summarized as follows:

1 **for** each pixel in image I_1
  run protanope simulation module in I_1 and **name** the resulting image I_2
2 **calculate** image E, where $E = abs(I_2 - I_1)$
3 **for** i=1 to m and **for** i=1 to n; // m and n is the x any size of image,
  if $E(i,j)>0.01*I_1(i,j)$ **then** $I_{AND}(i,j)=1$
  else $I_{AND}(i,j)=0$
4 **calculate** I_3: $I_3 = I_1 \cap I_{AND}$
5 **calculate** image $I_{correct}$, where: $I_{correct} = I_1 \cap (\neg I_{AND})$
6 **run** daltonization module in I_3 with matrix M and **name** the resulting image I_4
7 **run** protanope simulation module in I_4 and **name** the resulting image I_5

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8 **for** every pixel in I_5 **execute** RGB similarity checking module
if RGB_result =0 **then** continue with step 9
else if RGB_result =1 **repeat** step 6, modifying matrix M
9 **create** image I_{final}: $I_{final} = I_{correct} \cup I_4$

6 Conclusions

In this paper, an intelligent daltonization algorithm for the people suffering from protanopia is proposed. More specifically, an intelligent iteration technique is suggested for the selection of the adaptation parameters, taking into consideration a color clustering method which eliminates the possibility of color matching between the original and the daltonized image. The principals of this method could be modified in the future to provide better visual information in a color image for people that are affected from other color deficiencies. Moreover, a further extension of the method could be applied to video content. In the present form, this is not possible due to the fact that the algorithm is relatively time consuming. Indicatively, in a Pentium IV, 3.2 GHz, each iteration of the algorithm in Matlab when applied in a 24bit 300x300 image, lasts 2.1 seconds.

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