A color coding method for radiographic images

Xie-Qi Shi\textsuperscript{a}, Pehr Sällström\textsuperscript{b}, Ulf Welander\textsuperscript{a,*}

\textsuperscript{a}Department of Oral Radiology, Karolinska Institutet, Stockholm, Sweden
\textsuperscript{b}Department of Physics, University of Stockholm, Stockholm, Sweden

Abstract

A color scale was designed with an approach that combined both human visual response to color and physical properties of color. The design was initiated with a subjective evaluation of a 16 step color scale running from dark blue via magenta, orange to light yellow. The CIELUV chromaticity diagram was employed to verify the subjectively generated scale and to ensure that the differences in hue between the 16 steps was as equal as possible. The brightness of each step was adjusted to fit the function of the so-called \( L^* \), which represents the response of the human visual system to luminance. Preliminary results using a computer generated radiograph indicate improved perception in color-coded than in black-and-white radiographs. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Visualization; Pseudocolor; Grey to-color transformation

1. Introduction

A number of attempts have been made to replace the ordinary black-and-white scale of radiographs with a color scale. In theory, this should improve perception of small contrasts because the number of perceptible colors with different hue, brightness and saturation far exceeds the number of perceptible gray levels which are, in fact, no more than about one hundred for an average observer.

Clarke and Leonard \cite{1} give a review of three spectra commonly used to create color scales that may replace the gray scale. In all three spectra, the color scales follow the order of the hue series of the rainbow. Using this approach, perception will be affected by the fact that the visual system has a different sensitivity to different hues, being highest in the green part of the spectrum. Additionally, yellow is experienced as a brighter color than both green and red. As a consequence of the last fact, it follows that when gray levels at a certain value are replaced by green and brighter gray levels by yellow and red, original gray levels in a black-and-white radiograph will, in a image that is color coded according to the rainbow model, be perceived as increasing from green to yellow and decreasing from yellow to red. This does not correspond to the perception of the gray scale where brightness increases continuously from gray to white.

This phenomenon was also pointed out by Clark and Leonard \cite{1}

A proposed modification of the rainbow scale was presented by Lehmann et al. \cite{2}. The most important improvement was that the brightness order of the original gray scale was kept. However, the above-mentioned drawbacks with the rainbow model persist.

One often encounters color coding of radiographs that look highly arbitrary as regards hue ordering and much too exaggerated as regards brightness and saturation, of the colors to be satisfactory. In such cases, the color coding does not bring about any improvement in the legibility of the radiographic information. Since the gray scale is accepted in radiography and has worked well so far, color should be used to emphasize but not destroy the way a black-and-white radiograph appears.

In order to construct a color scale that would improve perception of low contrast details, a series of steps should be chosen that uses not only variation of brightness but also variation of hue and saturation.

The video display unit (VDU) of a color monitor is based on the RGB system, i.e. the three additive primary colors red, green and blue. The light emission of each one of the primaries can be varied independently. Thus the intensity level is governed by the video signal to the monitor, the signal being determined by three integers \( r, g \) and \( b \), specifying the level of light emission of the respective primary. At a certain combination of emission of the three primaries, the appearance on the screen, i.e. the additive mixture, will be gray. Usually, the monitor is adjusted so that gray corresponds to \( r = g = b \). Thus, a complete gray
scale, digitally coded as 8-bit data, i.e. 256 steps from 0 to 255, is produced by starting with \( r = g = b = 0 \); giving black, and increasing the signals to the three primaries in parallel steps until \( r, g \) and \( b \) are all 255, giving white. Any different balance between the \( r, g \) and \( b \) values will result in a chromatic color on the screen.

Let us consider the color coding problem from the point of view of the RGB cube, where the three primary colors are plotted in a three-dimensional graph with the values of \( r, g \) and \( b \) specifying the luminance contribution of the respective primary, offset on the three axes. As stated above, the straight line running diagonally from the black point \((0, 0, 0)\) to the white point \((255, 255, 255)\) represents the gray scale. A color coding scale using hues would be represented within the volume of the RGB cube by some curve connecting the same two points. One has reason to expect that the number of distinguishable steps along this curve would be greater than along the straight line of the gray scale. Thus, an appropriate color coding might improve the visual perception of radiographic contrasts. The aim of the present work is to present and discuss a method of defining such a curve suitable for the assessment of radiographic data.

2. Criteria

Radiographs are intended for being viewed by the human eye. Thus, it seems appropriate to apply aesthetic criteria for the design of a color scale to be used. With this principle in mind we settled on the following criteria:

- The main ordering principle of the points of the color scale should be that of increasing brightness. The hue aspect should act as a flavor to the series of colors making each step more pregnant, more individual, but not taking command.
- The hues should be chosen in such a way that the color scale runs from inherently dark hues to inherently light hues, i.e. from black, blue and magenta at one end to orange, yellow and white at the other end.
- To avoid exaggerated saturation, no color should be mixed from only two of R, G and B. There should always be some amount of excitation of all three phosphors of the monitor at any step of the scale except at black where all three equal zero. Pairwise additive mixtures tend to look more saturated than triple mixtures, thus breaking the aesthetic continuity of the scale.

When the second criterion is concerned, there are two possible series to choose between, one taking its route from blue via cyan and green, the other one running from blue through magenta, red, orange and yellow. The former scale is cool, the latter warm. As can be seen from Fig. 1, the warm scale gives the most articulated steps since the hue variation is greater along that series of colors. The use of a rainbow series of hues, or even the full color circle (Fig. 1), would destroy the natural linear brightness order since it means a periodic variation. A linearly increasing magnitude should not be artificially turned into a cyclic one.

3. Procedure

The method used for designing a color scale keeping the above listed criteria in mind was as follows.

First, a scale of 16 steps was set up on the display using a computer program designed by one of the authors (PS). The scale starts at black and ends in white running through dark blue, magenta, red, orange, and yellow. All steps were adjusted visually until the scale looked balanced as a whole which meant that each step came forth with the same distinctiveness while the perceptual difference between successive steps appeared to be the same all over the scale. Subjectively, the brightness increased evenly from black at one end to white at the other.

During the process of visual presetting of the scale, it was presented on the screen against a black background. The display was viewed under normal indoor daylight conditions while care was taken to avoid direct light on the screen as well as reflexes from windows and lamps.

When a visually satisfactory scale had been achieved the \( r, g \) and \( b \) values for the series of colors were taken over into a different section of the computer program where the corresponding color valencies in terms of the traditional CIE (1937) chromaticity diagram as well as in terms of the nowadays used CIELUV (1976) system were calculated and displayed as interactive plots, where the influence of any
change in \( r, g \) or \( b \) to the chromaticity could be immediately seen. The variables of the CIELUV color space are \( u, v \) and \( L^* \). The ordered pair \((u, v)\) is the chromaticity of the light, which corresponds to the perceived hue and saturation of the sample. \( L^* \) is a function of the luminance defined to correspond to the perceived brightness of the sample, which in our case is a delimited area on the screen, e.g. one step of the displayed scale.

The variables \( u, v \) and \( L^* \) are calculated from the \( r, g \) and \( b \) values as described below.

On the basis of visual judgment of how well data points fitted smoothly with a continuous curve in the chromaticity diagram, some steps of the scale were adjusted with respect to their \( r, g \) and \( b \) values. In addition to that, the scale was adjusted to become almost equally spaced in terms of \( L^* \).

Alternating between these different procedures, i.e. on one hand the procedure based on visual assessment by looking directly at the scale presented as a whole on the screen, and on the other hand the procedure based on the demand for a smooth course in the colorimetric diagrams and linearity in terms of \( L^* \), we finally settled on a scale that fulfilled the above mentioned criteria. The color scale, interpolated to 64 steps, is shown in Fig. 2, together with a gray scale with corresponding luminance steps.

The chromaticities of the steps of the color scale are shown in Fig. 3 as points in the CIE 1976 UCS (Uniform-Chromaticity-Scale) diagram. The points are seen to follow a smooth course.

### 4. Prototype color scale

The color scale that is shown in Fig. 2 is based on the \( r, g \) and \( b \) values given in Table 1 and shown graphically in Fig. 4, versus the gray scale. Data were fitted and interpolation performed by polynomials. Fig. 5 shows the corresponding curve in the RGB cube.

<table>
<thead>
<tr>
<th>Gray</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>26</td>
<td>16</td>
<td>63</td>
</tr>
<tr>
<td>42</td>
<td>45</td>
<td>24</td>
<td>84</td>
</tr>
<tr>
<td>55</td>
<td>70</td>
<td>29</td>
<td>103</td>
</tr>
<tr>
<td>69</td>
<td>98</td>
<td>33</td>
<td>119</td>
</tr>
<tr>
<td>83</td>
<td>128</td>
<td>37</td>
<td>132</td>
</tr>
<tr>
<td>98</td>
<td>160</td>
<td>41</td>
<td>140</td>
</tr>
<tr>
<td>114</td>
<td>195</td>
<td>48</td>
<td>141</td>
</tr>
<tr>
<td>130</td>
<td>223</td>
<td>65</td>
<td>136</td>
</tr>
<tr>
<td>147</td>
<td>244</td>
<td>93</td>
<td>120</td>
</tr>
<tr>
<td>164</td>
<td>254</td>
<td>126</td>
<td>104</td>
</tr>
<tr>
<td>181</td>
<td>255</td>
<td>159</td>
<td>96</td>
</tr>
<tr>
<td>199</td>
<td>253</td>
<td>190</td>
<td>104</td>
</tr>
<tr>
<td>217</td>
<td>246</td>
<td>218</td>
<td>133</td>
</tr>
<tr>
<td>236</td>
<td>246</td>
<td>240</td>
<td>188</td>
</tr>
<tr>
<td>255</td>
<td>255</td>
<td>255</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 1

The digital code values for the three primary colors of the RGB system shown in Fig. 2 together with the corresponding gray scale, i.e. a scale where \( r = g = b \). The values are valid for a gamma of 2.3.

![Fig. 2. Prototype of color scale displayed together with its corresponding gray scale.](image)

![Fig. 3. Chromaticity diagram according to CIE 1976 UCS. The 16 points represent the successive steps of the designed scale running from dark blue at the bottom via magenta up to yellow and then turning down ending at the white-point marked by a cross. The triangle is the region of chromaticities possible to reproduce on the VDU, i.e. as additive mixtures of the three primaries R, G, B, situated at the corners of the triangle.](image)

![Fig. 4. Digital \( r, g, b \) values defining the color scale relative to a gray scale coding \( r = g = b \). \( o \) denotes \( r, + \) denotes \( g \) and \( \Box \) denotes \( b \).](image)
5. Device independent definition of the color scale

The \( r \), \( g \) and \( b \) values shown in Fig. 4 are valid for the particular VDU that was used in the procedure to determine this particular color coding scheme, or any VDU comparable to that one. The luminance of a certain point on the VDU screen is not linear in \( r \), \( g \) and \( b \), but approximately a power function of them. For instance, if we denote the radiant output relative to maximum output, from the red phosphor \( I(r) \), then \( I(r) = (r/255)^3 \), where \( \gamma = 2.30 \) in our case. Moreover, the white balance may vary appreciably from monitor to monitor. In our case, the correlated color temperature of the VDU was nominally set at 9300 K.

To generalize our result, we have to express it in device independent variables. This may be performed by transforming the data into the CIE colorimetric standard reference system. In Table 2 the so-called tristimulus coordinates \( X \), \( Y \), \( Z \) of the CIE 1931 system are presented for the 16 steps of the scale. The luminance, \( Y \), has been normalized to 100 cd/m\(^2\) at the white end point of the scale (in our case it was 105 cd/m\(^2\)).

The hue and saturation of the steps of the color scale are defined by the relationship of \( X \) and \( Z \) to \( Y \) and can be visualized by help of the CIE 1976 UCS (Uniform Color Space) chromaticity diagram (Fig. 3).

![Fig. 5. Digital \( r \), \( g \), \( b \) values displayed in an RGB cube.](image)

![Fig. 6. The relation between a digital gray scale, with \( r = g = b \)-values increasing in equal steps and a perceptually uniform scale, in terms of \( L^* \). The circles are the 16 steps of our prototype scale.](image)

### Table 2

<table>
<thead>
<tr>
<th>( X )</th>
<th>( Y )</th>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.065</td>
<td>0.07</td>
</tr>
<tr>
<td>1</td>
<td>1.287</td>
<td>0.738</td>
</tr>
<tr>
<td>2</td>
<td>2.801</td>
<td>1.617</td>
</tr>
<tr>
<td>3</td>
<td>5.284</td>
<td>2.989</td>
</tr>
<tr>
<td>4</td>
<td>8.91</td>
<td>4.976</td>
</tr>
<tr>
<td>5</td>
<td>13.78</td>
<td>7.692</td>
</tr>
<tr>
<td>6</td>
<td>20.08</td>
<td>11.25</td>
</tr>
<tr>
<td>7</td>
<td>28.05</td>
<td>15.94</td>
</tr>
<tr>
<td>8</td>
<td>35.83</td>
<td>21.35</td>
</tr>
<tr>
<td>9</td>
<td>42.88</td>
<td>28.12</td>
</tr>
<tr>
<td>10</td>
<td>48.27</td>
<td>36.19</td>
</tr>
<tr>
<td>11</td>
<td>52.68</td>
<td>45.67</td>
</tr>
<tr>
<td>12</td>
<td>57.62</td>
<td>56.68</td>
</tr>
<tr>
<td>13</td>
<td>63.64</td>
<td>69.33</td>
</tr>
<tr>
<td>14</td>
<td>74.95</td>
<td>83.92</td>
</tr>
<tr>
<td>15</td>
<td>95.36</td>
<td>100</td>
</tr>
</tbody>
</table>

### Colorimetric calculations

The calculation behind Fig. 2, as well as the data of Table 2, proceeds in two steps. First, \( X \), \( Y \) and \( Z \) are calculated and from \( u \), \( v \) and \( L^* \). The calculation presupposes knowledge of the colorimetric properties of the employed display. Using a Spectra Scan PR650 spectrophotometer (Photo Research, Inc, Chatsworth, CA, USA), we measured \( X \), \( Y \) and \( Z \) as functions of the digital excitation levels of each separate phosphor. For instance, \( X_g(r) \) is obtained by putting \( g = 0 \), \( b = 0 \) and varying \( r \), measuring the emitted light at a number of levels between 0 and 255. We also measured the background luminance of the screen obtained at \( r = g = b = 0 \), and subtracted this each one of the measured function in order to make them 0 at digital excitation level 0.

By definition \( X_g(r) = 0 \) when \( r = 0 \) etc.. We denote the tristimulus values of the background \( X_C \), \( Y_C \) and \( Z_C \). Then:

\[
X = X_g(r) + X_C(g) + X_b(b) + X_C
\]

\[
Y = Y_g(r) + Y_C(g) + Y_b(b) + Y_C
\]

\[
Z = Z_g(r) + Z_C(g) + Z_b(b) + Z_C
\]

In our case, \( X_C = 0.067 \), \( Y_C = 0.070 \) and \( Z_C = 0.030 \). These values were also used to calculate \( u \), \( v \) and \( L^* \) of CIELUV color space using the following expressions [3]:

\[
u = 4X/(X + 15Y + 3Z)
\]

\[
v = 9Y/(X + 15Y + 3Z)
\]

\[
L^* = 116(Y/Y_0)^{1/3} - 16 \quad \text{for } Y/Y_0 > 0.008856
\]

\[
L^* = 903.3(Y/Y_0) \quad \text{for } Y/Y_0 < 0.008856
\]

\( Y \) is the luminance and hence proportional to the physical radiance of the screen, \( Y_0 \) is the maximum obtained at \( r = g = b = 255 \). \( L^* \) is defined so as to correspond to perceptually equal steps in increasing brightness employing the parameter ‘Value’ of the Munsell system as standard [4]. The normalization constants are chosen so as to make \( L^* \) vary between 0 and 100. The steps of our prototype scale, as
presented in Tables 1 and 2 and in Figs. 3–5, correspond to equal steps in $L^*$ since this was found reasonable in our initial visual evaluation of the scale. This means that a gray scale, constructed by putting $r = g = b = w$, will not be perceptually optimum. However, for gamma values around 2.3, the deviation concerns mainly the darkest levels of the scale, where equal steps in gray level will correspond to smaller steps in visual brightness than at higher levels, i.e. for gray level above 60 (Fig. 6).

7. Application

To apply the suggested color coding scheme to a particular VDU its colorimetric properties must be known, i.e. the nine functions $X_R(r), X_G(g)$ etc. in Eqs. (1a)–(1c), in order to enable a transformation from given $X, Y, Z$ values to the digital code $r, g, b$ pertinent to a certain device. For further details, see Appendix A.

If detailed knowledge of a certain VDU is not available, it will be possible to use the $r, g, b$ values of our prototype scale. The $r, g, b$ integer values for the 16 reference points are given in Table 1. Interpolating between these values should in practice provide a suitable approximation. However, it should be kept in mind that they were intended for use with a VDU having a gamma value of 2.3 and a color temperature of 9300 K. If a certain monitor has a gamma of, e.g. 2.2, which is quite common this only demands a minor change in the $r, g, b$ values. Should a monitor be set at 6500–7000 K, the $r, g, b$ values suggested here should still be suitable due to chromatic adaptation of the human visual system. The coding may, of course, be adjusted following the principles for the construction of an appropriate scale stated at the beginning of this paper.

8. Tentative evaluation

The color scale was used for coding a computer generated test image in order to find out whether or not contrast sensitivity had been improved as compared to presenting the image in black-and-white. The 8-bit test image had a series of columns with increasing gray levels forming the background to 11 rows of circular dots that from top to bottom, in steps of 1, had increasing contrast relative to the columns. Subjectively evaluated by the investigators, contrast perception was definitely better in the color coded than in the original black-and-white image (Fig. 7). An example of an intra-oral radiograph is presented as coded both in black-and-white and in color, in Fig. 8.

9. Discussion

In this paper, a new color scale that may replace the gray scale is presented. This scale preserves the light intensities of original black-and-white radiographs taking into account the response of the human visual system. Furthermore, it takes into account the fact that yellow is experienced as a brighter color than all other hues, and saturated blue and violet colors are in practice relatively dark. Thus, the scale was constructed to run from inherently dark to inherently bright colors, i.e. from black via blue, magenta, red, yellow red, yellow to white. The last feature does not seem to have been incorporated in previously suggested color scales that has often applied the order of colors in the rainbow: blue, green, yellow, red and red. This rainbow scale causes a cyclic variation of experienced colors. An additional important characteristic of the present color scale is that the hues are combined utilizing all the three primaries, red, green and blue, which reduces exaggerated saturation of anyone of the hues.
Work is in progress to evaluate the color scale with respect to perception of low contrast. Preliminary results using the perceptibility curve test indicate that color-coded test radiographs may decrease the perception threshold to some extent. Under all circumstances, it performs at least as good as the original black-and-white radiographs [6].

Applying the color scale to the diagnosis of approximal caries lesions in an in vitro study demonstrated no statistically significant difference in diagnostic accuracy between original and color-coded radiographs [7]. Referring to the results obtained with the perceptibility curve test a certain difference should have been expected. An explanation for the lack of difference may possibly be found in the fact that viewers were unfamiliar with interpreting color-coded radiographs where the radiographic information is presented in a different way. Should this be the case, training ought to improve diagnostic accuracy. It is a well-known fact that perceptual learning has a great impact on extracting information from any type of images.

Since the gray scale has worked well in radiography during a long period of time, it is not the intention of the authors that the suggested scale should be used to substitute the gray scale in ordinary radiographic work. Instead, the color scale may be used as an approach to enhance radiographic information for certain diagnostic purpose. Further studies will focus on the application of this color-coding method for different diagnostic tasks.

Acknowledgments

The authors wish to express their sincere thanks to Lennart Högman, PhD, Department of Psychology, University of Stockholm, Sweden, for assisting in measuring the properties of the monitor used in the present work.

Appendix. Calculation of $r$, $g$, $b$ values from knowledge of $X$, $Y$, $Z$

In order to calculate the series of $r$, $g$, $b$ values, pertinent to a particular, VDU certain facts about its color reproduction properties must be known. If the nine functions $X_R(r)$, $X_G(g)$ etc. used in expressions (1a)–(1c) above are measured, one may use a recursive method to find the $r$, $g$, $b$ values that correspond to given $X$, $Y$, $Z$ as described by Tonnquist and Heng [5].

A simpler method, quite satisfactory in practice, is based on the following assumptions:

- The spectral distribution of the light emitted from each of the phosphors is constant, i.e. independent of the excitation level. This means that the chromaticity for each phosphor is constant. It is sufficient to measure it at the maximum, i.e. at the level 255.
- The excitation function may be approximated by a power function, i.e. the intensity of the emitted light may be expressed by $I(r) = (r/255)\gamma R$ for the red phosphor and $I(g) = (g/255)\gamma G$ and $I(b) = (b/255)\gamma B$ for the green and blue phosphors, respectively. Moreover, it is preferable that the three gamma values are the same, which means that the excitation function is one and the...
same for R, G and B. Otherwise the gray-scale will not be
defined by the simple criterion \( r = g = b \).

Accepting this model, Eqs. (1a)–(1c) may be re-written as:

\[
X = X_R I(r) + X_G I(g) + X_B I(b) + X_C \tag{A1}
\]
\[
Y = Y_R I(r) + Y_G I(g) + Y_B I(b) + Y_C \tag{A2}
\]
\[
Z = Z_R I(r) + Z_G I(g) + Z_B I(b) + Z_C \tag{A3}
\]

where \( X_R, X_G, X_B \) etc. are nine constants determined by
measuring the tristimulus values on the screen for \( r = 255, g = b = 0 \) and \( r = 0, g = 255, b = 0 \) and \( r = 0, g = 0, b = 255 \), respectively.

Given \( X, Y, Z \), Eqs. (A1)–(A3) may be solved for the
unknown excitations \( I(r), I(g) \) and \( I(b) \). Then, \( r, g \) and \( b \) can be calculated by inversion of the power function:

\[
r = 255 I^{1/\gamma}
\]

If you know only the chromaticities of the three primaries
and the white point of your monitor, the matrix elements
above can be calculated from this information.

The monitor we used for evaluating the color coding
scale had the following chromaticities for the phosphors and
the white point

\[
\begin{array}{ccc}
x & y \\
\text{Red} & 0.622 & 0.343 \\
\text{Green} & 0.287 & 0.608 \\
\text{Blue} & 0.150 & 0.068 \\
\text{White} & 0.283 & 0.296 \\
\end{array}
\]

The matrix \( X_R, X_G, X_B \) etc. used for calculating \( X, Y, Z \) was

\[
\begin{pmatrix}
40.99 & 33.20 & 25.66 \\
22.60 & 70.45 & 11.66 \\
2.337 & 12.27 & 133.9 \\
\end{pmatrix}
\]

References