Colour vision and computer-generated images

Michael Ramek
Institut für Physikalische und Theoretische Chemie, Graz University of Technology,
8010 Graz, Austria
michael.ramek@tugraz.at

Abstract. Colour vision deficiencies affect approximately 8% of the male and approximately 0.4% of the female population. In this work, it is demonstrated that computer generated images oftentimes pose unnecessary problems for colour deficient viewers. Three examples, the visualization of molecular structures, graphs of mathematical functions, and colour coded images from numerical data are used to identify problematic colour combinations: red/black, green/black, red/yellow, yellow/white, fuchsia/white, and aqua/white. Alternatives for these combinations are discussed.

1. Introduction
Human colour vision is made possible by three types of colour sensitive cones in the retina with absorption maxima at 558.4±5.2 nm, 530.8±3.5 nm, and 419.0±3.6 nm [1]. According to wave length range, these cones are commonly called L, M, and S or simply red, green, and blue. The red cones are modifications of the green ones, which differ only in 14 amino acids of a 364 amino acid protein [2]. Therefore, the red and the green receptors overlap in a significant spectral range. It is this overlap, which enables us to distinguish various shades of green, yellow, and red.

Changes in the spectral properties of these colour receptors may be caused by genetic reasons or induced by illness (either directly or as a medication side effect). While the former reason affects mostly males [3] at a rate of about 8% [4], the latter affects both sexes at equal rate. Minor changes often remain undetected for a long time, whereas severe cases (“colour blindness”) are usually noticed by those affected. The first detailed scientific report of colour blindness is the one given by John Dalton [5]. Although based on a wrong assumption, namely coloured liquid in the eyeballs, Dalton’s report made this kind of deficiency widely known. Moreover, those affected became aware that their situation is not due to an individual inability, but rather a condition that others are also subject to. The long-lasting impact of Dalton’s report is manifested by the fact that, until today, colour blindness is called “daltonism” in a number of languages.

In today’s world, computers are used for more and more purposes. Information retrieval via the world wide web or computer-based presentations have become routine tasks. Astonishingly often, colour
deficient viewers miss part of the information on monitors, video walls, or projections: a person, e. g., who is unable to see red, can neither spot a red laser pointer on a screen nor read red letters on dark background [6]. Photographs of real life situations are usually less problematic than computer-generated images, which are the focus of this work. Based on a number of examples from the area of quantum chemistry, for which the author had data at hand, a few rules of thumb are developed to avoid such pitfalls.

2. Colour vision types
The generally accepted types of colour vision are listed in table 1 together with approximate frequency values. It has to be stressed that these frequencies are global average values, ethnic groups may have different values that depend on the specific circumstances and history.

Table 1. Colour vision types with approximate frequency values. With the exception of achromatopia, which is not sex-linked, these values refer to the male population. Different ethnic groups may have deviating frequency values.

| Type            | Cones Affected                  | Effect on Vision                                                                 |
|-----------------|---------------------------------|----------------------------------------------------------------------------------|
| normal (91%)    | red, green, and blue function normally | normal trichromatic vision                                                      |
| deuteranomalia (5%) | green cones are red-sensitive | green is perceived as black, red and yellow appear identical, turquoise as blue |
| protanomalia (1%) | red cones are green-sensitive | green is perceived as a shade of yellow, red as black, purple as blue          |
| protanopia (1%)  | red cones are insensitive       | red is perceived as black, green and yellow as identical, purple as blue        |
| deuteranopia (1%) | green cones are insensitive     | green is perceived as black, red and yellow appear identical, turquoise as blue |
| tritanopia (10^-3%) | blue cones are insensitive      | blue is perceived as black, purple and red are identical, turquoise appears green |
| monochromatopia (10^-4%) | only blue cones function normally | red, yellow, and green are perceived as black                                  |
| achromatopia (10^-5%) | all colour cones are insensitive, only rods (night vision) function normally | day-blindness                                                                    |
While the different types listed in table 1 may already appear confusingly complex at first, individual situations may even be more complex. Human vision is a brain skill that is developed step by step in the first few months of a child’s life. During this process, the brain learns to optimally discern the incoming signals, and occasionally an individual pigmentation results in unique vision abilities [7].

Despite the broad range of individual cases, several types can be discussed together: deuteranomaly and deuteranopia, e.g., are different conditions that are caused by different pigmentation patterns of the retina cones, yet both can be summarized as a deuteran group, a significant number of people who are unable to see green. Similarly, protanomaly and protanopia constitute a protan group of people, who are unable to see red. Cases that involve blue occur at a much smaller frequency.

3. Computer monitors and software

In painting or printing, subtractive colour mixing takes place: a mixture of all colours yields some kind of black. Moreover, contextual influences, like reflectance differences or the type of illumination, may alter the visual impression. In contrast, computer or TV monitors are light sources with an additive mixing: all colours together yield white. Monitors emit light that consists of a few frequencies only.

Table 2. The colours defined for use in hypertext documents [8], with their red, green, and blue components.

| colour name | R   | G   | B   |
|-------------|-----|-----|-----|
| black       | 0%  | 0%  | 0%  |
| gray        | 50% | 50% | 50% |
| silver      | 75% | 75% | 75% |
| white       | 100%| 100%| 100%|
| maroon      | 50% | 0%  | 0%  |
| red         | 100%| 0%  | 0%  |
| green       | 0%  | 50% | 0%  |
| lime        | 0%  | 100%| 0%  |
| navy        | 0%  | 0%  | 50% |
| blue        | 0%  | 0%  | 100%|
| purple      | 50% | 0%  | 50% |
| fuchsia     | 100%| 0%  | 100%|
| olive       | 50% | 50% | 0%  |
| yellow      | 100%| 100%| 0%  |
| teal        | 0%  | 50% | 50% |
| aqua        | 0%  | 100%| 100%|
Figure 1. Emission spectra (intensity [arbitrary units] vs. wave length [nm]) of the R-channel of two RGB displays: a cathode ray tube monitor (black, lower graph) and a LCD monitor (gray, upper graph).

Figure 1 demonstrates this via the emission spectra of the red channel of two technically quite different commercial monitors. These few frequencies are specifically designed to exclusively excite the red, green, and blue receptors in the human eye. Contextual influences, which give important clues in the normal visual process, are not present in computer generated images, i.e., the light emitted by the three colour channels of the monitor is the only relevant information that reaches the observer's eye.

With these three channels, almost all colours can be generated that the human eye is capable of seeing. In practice, however, authors of software packages or software standards tend to use only one- or two-dimensional subspaces of this three-dimensional colour space. Table 2 lists the basic colours defined in the hypertext markup language standard [8] as an example. These colour names are also used in this work.

Since the majority of colour deficient viewers is either unable to see red or unable to see green, an easy method of predicting the effect of colour blindness would be to unplug the red or green channel (some older monitors indeed do have cables with three individual plugs). The same effect can be simulated by graphic programs that allow an intensity adjustment of the RGB channels. Reducing the red or green channel to zero intensity will change white to an intense colour (aqua or fuchsia in the notation of table 2), which looks strange to a person with normal trichromatic colour vision. The brain of a red blind person, however, that developed its visual skills under the absence of a red retinal pigment, will classify aqua a normal colour, often seen before. The essential point of this simple simulation is not the strange colour, to which white is transformed—the essential point is that any aqua-coloured display on a white background will be transformed to an aqua display on an aqua background that becomes invisible. A red blind person will, indeed, have difficulties seeing an aqua display on a white background, as it will have difficulties seeing red text on black background [6]. Hence, this simple simulation can be used as a rigorous test: If essential features get obscured by such a manipulation, chances are good that a non-negligible fraction of viewers will have difficulties.

As a general rule, all colours made up by only one non-zero component and all colours that consist of two 100% components are problematic. This includes the following:
a) **Red/black and green/black:** these combinations often occur when a black background is used. Figure 2 exemplifies this by means of a Rasmol [9] visualization of a molecular structure, using the default colour scheme of this program. In this colour scheme, some atoms remain invisible for *protan* or *deuteran* viewers, since for them these atoms are displayed in black—the same colour as the image background.

![Figure 2](image)

**Figure 2.** Visualization of the most stable 4-chloro-3-indole acetic acid conformer [10] by Rasmol [9] using the default color scheme of that program as seen by a person with normal color vision (top), by someone unable to see red (middle), and by someone unable to see green (bottom). Atoms depicted in these colors blend in with the black background.
b) Yellow/white, aqua/white, and fuchsia/white: these colour combinations often occur in graphs on white background. Figure 3 gives an example using the approximation of Slater-type orbitals by a number of Gaussian functions [11]. While the author has to admit that this figure uses intentionally chosen colours, figure 2 of [12] is another recent example, the authors of which certainly cannot be blamed for an intention to choose bad colours.

Figure 3. Approximation of a 1s Slater-type orbital by various linear combinations of Gaussian functions [11] as seen by someone with normal color vision (top). A person unable to see red can perceive only a subset of this information (middle), while a green-blind person will perceive a different subset (bottom).
c) **Red/yellow:** this colour combination often occurs in connection with rainbow-like colour coding, where red gradually turns into yellow and on into green and blue. Such colour coding is often used for maps, thermo imaging, or the visualization of electric properties. Figure 4 gives an example using the RHF potential energy surface of β-alanine [13] in the vicinity of an interesting conformation. Other recent examples are figures 1–3 of [14] as well as figures 2 and 8 of [15]. Figures 5 and 6 show the same energy surface as figure 4 without the red and the green component, respectively.

![Figure 4](image)

**Figure 4.** Relative energy (kcal/mole) of the vicinity of the two mirror-symmetrical conformers of neutral β-alanine, which are stabilized by an intramolecular hydrogen bond. The map shows RHF/4-31G energies[13] as a function of the amino group orientation (torsion angles H–N–C–C, ordinate) and the backbone orientation (torsion angle C–C–N, abscissa) in the colour coding indicated. The reaction does not pass the achiral structure of C₅ symmetry, which corresponds to the center of the image; instead, two equivalent chiral reaction paths exist, both of which keep the hydrogen bond intact.
**Figure 5.** Figure 4 as seen by a red blind person. The point of achirality in the center of the surface is clearly visible, but a detailed knowledge of potential energy surface properties is necessary to recognize that it is a second order saddle point.

**4. Alternatives**

Most problematic colour combinations (red/black, green/black, red/yellow) can be avoided by changing black or yellow to some grey tone. A change of the background colour may already be sufficient: figure 7 shows the same molecule as figure 2, but with a grey background. This small change is enough to transmit significantly more information.

Colour combinations including yellow can be resolved by a transformation of yellow to off-white or grey. For RGB triples in the range [0, 255], such a transformation is very effectively performed by the following code segment, in which a reduction factor is determined from the absolute value of the R–G difference (which is zero for yellow or blue, and up to 255 for red or green tones); subsequently the R and G signals are reduced, whereas the B signal is increased if less than 255.

```plaintext
n = 7  # yellow → off-white; use smaller values for yellow → light grey
f = max(0, abs(B–255) – abs(R–G)) / (2 × n + 1) × 255
B = min(255, B + n × f × (R+G))
R = (1–f) R
G = (1–f) G
```
Such a transformation is easy to incorporate into programs that generate RGB codes from numerical data as an alternative to a redefinition of the underlying grey scale to colour conversion. The effect can be seen in figure 8, which shows the same energy surface as figure 4, but with yellow converted to light grey (using the above code segment with $n = 3$). Figure 9 shows this transformed image without the red and the green component. Again, for colour deficient viewers significantly more information is transported by these figures.

The colours yellow, aqua, and fuchsia pose problems in connection with white background. For graphs of mathematical functions, data recordings, ... colour should therefore not be the only means to distinguish different entries. The use of different symbols (open and full circles, squares, triangles, ...) or line styles (solid, dotted, dashed, ...) in traditional black and white figures is an unproblematic way of presentation.

![Figure 4 as seen by a green blind person. The second order saddle point in the center of the image is completely hidden in a broad area of uniform color.](image_url)
Colour combinations that are easy to distinguish for most viewers and hence can be recommended, when strong colour contrast is desired, are: black/white, black/yellow, blue/white, blue/yellow. Pastel colours in which all RGB components are $> 65\%$ and different from each other are usually good choices for background colours in presentations, when visual clues to related or opposed topics or areas are intended.

Figure 7. Figure 2 with a different background color. For people, who cannot see red or green, atoms in these colors still appear black, but the shape and structure of the molecule remains clearly recognizable.
Figure 8. Figure 4 with yellow converted to grey (see text for details of this transformation).

Acknowledgement
The author is grateful to Drs. Karl Gatterer and Elmar C. Fuchs from the Graz University of Technology for recording the emission spectra in figure 1.

References
[1] Dartnall H J A, Bowmaker J K and Mollon J D 1983 Proc. Roy. Soc. London. B, Biol. Sc. 220 115-30
[2] Natans L, Thomas D and Hogness D S 1986 Science 232 193-202
[3] Bell J and Haldane J B S 1937 Proc. Roy. Soc. London. B, Biol. Sc. 123 119-50
[4] Birch J 1993 Diagnosis of defective colour vision (Oxford: University Press) p 46
[5] Dalton J 1798 Mem. Literary Philos. Soc. Manchester 5 28-45
[6] Romano P E 1998 Ophthalmol. 105 1797
[7] Jameson K A, Highnote S M and Wasserman L M 2001 Psychosom. Bull. Rev. 8 244-61
[8] Raggett D, Le Hors A and Jacobs I 1999 HTML 4.01 Specification. http://www.w3.org/TR/html4/
[9] Sayle R and Milner-White E J 1995 Trends in Biochem. Sci. 20 374-76
[10] Ramek M, Tomič S and Kojić-Prodić B 1996 Int. J. Quant. Chem. 60 1727-33
[11] Hehre W J, Stewart R F and Pople J A 1969 J. Chem. Phys. 51 2657-64
Figure 9. Figure 8 as seen by red- or green blind persons. In contrast to figures 5 and 6, the center of the image is clearly recognizable as a local maximum in this two-dimensional map in both cases.
[12] Lele B S, Murata H, Matyjaszewski K and Russell A J 2005 Biomacromolecules 6 3380-7
[13] Ramek M 1990 J. Mol. Struct (Theochem) 208 301-55
[14] Jones H G, Stoll M, Santos T, de Sousa C, Chaves M M and Grant O M 2002 J. Exp. Botany 53 2249-60
[15] Aksimentiev A and Schulten K 2005 Biophys. J. 88 3745-61