# IDI - Visual Design - Color

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# Contents

# 1 Color

## 1.1 Introduction

Light enters the eye as spectrum of colors, distributed by wavelength. This spectral distribution function impinges on the retina in the back of the eye and is absorbed by the cones. Human beings have three types of cones, which respond to different wavelengths of light. These are called either long, medium and short wavelength cones, or, correspondingly, red, green and blue cones. Each cone absorbs light and sends a signal to the brain. That is, the spectrum of light is encoded into three values that correspond to the amount of light absorbed by each type of cone. This is the principle of trichromacy— human vision is 3 dimensional.

It should be clear that the actual distribution of the spectrum is only indirectly "seen" by the eye. The response of each cone can be encoded as a function of wavelength (the spectral response curve for the cone). Multiplying the spectrum by such a function and integrating produces the signal that is sent from the eye to the brain. Different spectra can produce the same signal, and as such, will "look the same." This principle is called *metamerism*.

The principle of metamerism underlies all color reproduction technologies. Instead of reproducing the spectral stimulus, they create an equivalent response, or metameric match by mixing primary colors in a controlled way.

Trichromacy and metamerism can also be applied to the problem of measuring color. It is important in many industries to be able to measure colored materials. If we can create an instrument that responds in the same way as the human eye, we can have an impartial observer to define when colors match. From the discussion above, it seems obvious to fit an instrument with filters and sensors that behave like the cones. However, the precise definition of the cone response was not known until very recently. The science of color measurement is much older, and is based on experiments involving matching colors with sets of three primary lights. This is called colorimetery.

## 1.2 Colorimetery

The color matching experiments that underlie colorimetery are constructed as follows. Choose three primary lights (call them red, green and blue). Then, take a set of reference colors such as the monochromatic colors of the spectrum, or those generated by filtering a white light. For any set of three independent primaries, you can match any other color. Period. The only requirement is that you allow the primaries to go negative. In a physical matching experiment, this means that you shine the "negative" primary on the sample to be matched. This is a remarkably useful result. It means we can create a representation for color based on three primary lights. Any color can be defined as a set of three numbers that correspond to the power of the primaries. These three numbers are called the tristimulus values for the color.

How do we know what primary values match a particular color? Clearly we cannot perform the color matching experiment on all possible spectra. The answer is to use the fact that colored light is additive. A spectrum can be constructed by adding a number of monochromatic lights together. This seems obvious, but what is less obvious is that the amount of the primaries needed to match colored light is also additive. Specifically, let the primaries be R, G and B. Let the spectrum be S. If RGB1 matches S1, and RGB2 matches S2, then RGB1+RGB2 will match S1+S2. This principle was first formalized by Grassman, it is called Grassman' s law.

To define the primaries for an arbitrary color, we use Grasman's law to construct a set of color matching functions for the primaries. We perform the color matching experiment on each of the monochromatic spectral colors (sampled every 2 nm, for example). We use the result to create a set of three functions, one for each primary. To determine the amount of the primaries needed to match a particular spectrum, multiply the spectrum by the color matching functions and integrate. Three multiplications and three integrations, and you have the match. As all the functions described are sampled, this process is quite simple to implement.

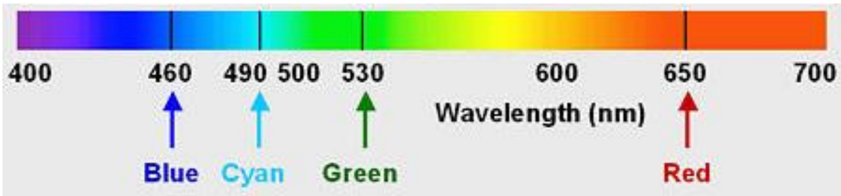
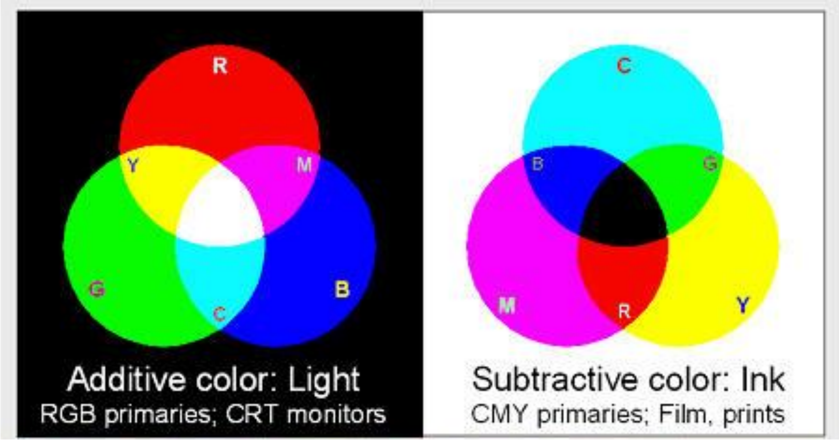



**Figure 9:** Visible light spectrum.

The human eye is sensitive to electromagnetic radiation with wavelengths between about 380 and 700 nanometers (see Figure 9). This radiation is known as light. The visible spectrum is illustrated on the right. The eye has three classes of color-sensitive light receptors called cones, which respond roughly to red, blue and green light (around 650, 530 and 460 nm, respectively). A range of colors can be reproduced by one of two complimentary approaches (also shown in Figure 10):

- **Additive color:** Additive color systems reproduce the red, green and blue parts of the image by adding together red, green and blue lights, starting with darkness (black). Such systems include monitors, liquid crystal displays (LCD) and digital projectors. The traditional additive color reproduction industry is television, though scanned graphics displayed on a monitor may be more familiar to this audience. Adding R and G light makes yellow (Y). Similarly, G + B = cyan (C) and R + B = magenta (M). Combining all three additive primaries makes white.
- **Subtractive color:** Subtractive color systems filter the red, green and blue components of the image from white light. To do this, they use colored filters that in theory modulate only the red, green and blue components of the spectrum. The filter that passes green and blue but modulates red appears cyan. Similarly the green-modulating filter appears a purplish-red called magenta, and the blue-modulating filter is yellow. Therefore, the primaries of a subtractive reproduction system are said to be cyan, magenta and yellow. In printing, black ink is added as well, to

improve the contrast. The advantage of subtractive color systems is that they use a single, white light source instead of three colored ones. Furthermore, for reflection




prints, this light is simply the light in the room.

**Figure 10:** Additive and subtractive colors.

Unfortunately, ideal C, Y and M inks don't exist; the subtractive primaries don't entirely remove their compliments (R, B and G). This isn't a problem for film, where light is transmitted through three separate dye layers, but it has important consequences for prints made with ink on reflective media (i.e., paper). Combining C, Y and M usually produces a muddy brown. Black ink (K) must be added to the mix to obtain deep black tones. CMYK color is highly device dependent. There are many algorithms for converting RGB to CMYK. Photographic editing should be done in RGB (or related) color spaces. Conversion to CMYK (usually with colors added to extend the printer color gamut) should be left to the printer driver software.

You can obtain a wide range of colors, but not all the colors the eye can see, by combining RGB light. The gamut of colors a device can reproduce depends on the spectrum of the primaries, which can be far from ideal. To complicate matters, the eye's response doesn't correspond exactly to R, G and B.

## 1.3 Color Depth

When we represent a color, we will have a higher precision the higher the number of bits we devote to its representation. The number of bits per pixel that can be displayed on a computer screen is called color **depth** and it is actually 24 bits per pixel. Initially, computer screens had only a single bit per pixel, and therefore only two colors were representable.

Although there have been quite a long since we have had **true color**, that is, 8 bits per color channel (16M of different representable colors), many mobile devices do not have this resolution due to many factors such as screen technologies or costs.

The actual colors that can be represented may vary because on short depth representations we may color palettes, that is, a certain code represents a color taken from a codebook.

Since each bit represents 2 colors, it is easy to work out the number of colors for the various color depths. The number of possible colors would be 2 to the power of the number of bits per pixel: A color depth of 4 bits would be 2 times itself 4 times: $2^4$ = 16 colors A color depth of 8 bits would be 2 times itself 8 times: $2^8$ = 256 colors. A color depth of 24 bits would be 2 times itself 24 times: $2^{24}$ = 16,777,216 colors.

## 2 Color models

If you lighten or darken color images you need to understand how color is represented. Unfortunately there are several models for representing color.

### 2.1 RGB

The RGB model forms its gamut from the primary additive colors of red, green and blue. When red, green and blue light is combined it forms white. Computers generally display RGB using 24-bit color. In the 24-bit RGB color model there are 256 variations for each of the additive colors of red, green and blue. Therefore there are 16,777,216 possible colors (256 reds x 256 greens x 256 blues) in the 24-bit RGB color model.

In the RGB color model, colors are represented by varying intensities of red, green, and blue light. The intensity of each of the red, green and blue components is represented on a scale from 0 to 255 with 0 being the least intensity (no light emitted) to 255 (maximum intensity). For example in the above RGB chart the magenta color would be R=255 G=0 B=255. Black would be R=0 G=0 B=0 (a total absence of light).

Sometimes RGB color space is represented by a cube, such as in Figure 11.

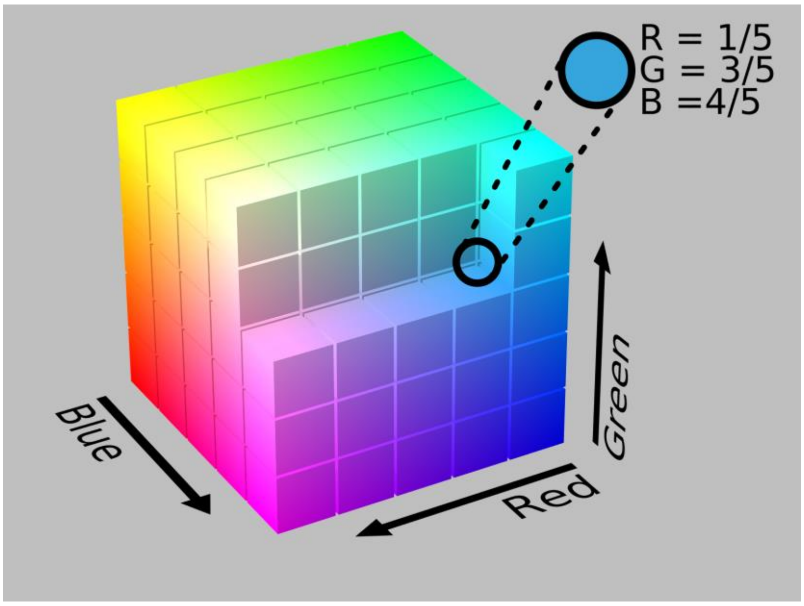



**Figure 11:** The RGB color cube.

There are actually a number of RGB color spaces-- sRBG, Adobe RGB 1998, Bruce RGB, Chrome 2000, etc., differing from each other in the purity of their primary colors, which affects their gamut, they range of colors they represent.

## 2.2 CMY(K)

CMYK is a subtractive color model used in color printing. The CMYK printing method is also known as "four-color process" or simply "process" color. All of the colors in the printable portion of the color spectrum can be achieved by overlapping "tints" of cyan, magenta, yellow and black inks. A tint is a screen of tiny dots appearing as a percentage of a solid color. When various tints of the four colors are printed in overlapping patterns it gives the illusion of continuous tones - like a photograph. Theoretically, and to an extent practically, black can be produced by mixing the magenta, cyan, and yellow – the subtractive primaries. But this is not suitable if we require a high quality print. To achieve higher quality, CMYK additionally uses black ink for coloring the print.

The CMYK model forms its gamut from the primary subtractive colors of cyan, magenta and yellow. When cyan, magenta and yellow inks are combined it forms black - in theory. However, because of the impurities in ink, when cyan, magenta and yellow inks are combined it produces a muddy brown color. Black ink is added to this system to compensate for these impurities.

In the CMYK color model, colors are represented as percentages of cyan, magenta, yellow and black. For example, white would be 0% cyan, 0% magenta, 0% yellow and 0% black (a total absence of ink on white paper).

The relationship between CMYK and RGB is shown in the CMYK color wheel in Figure 12.

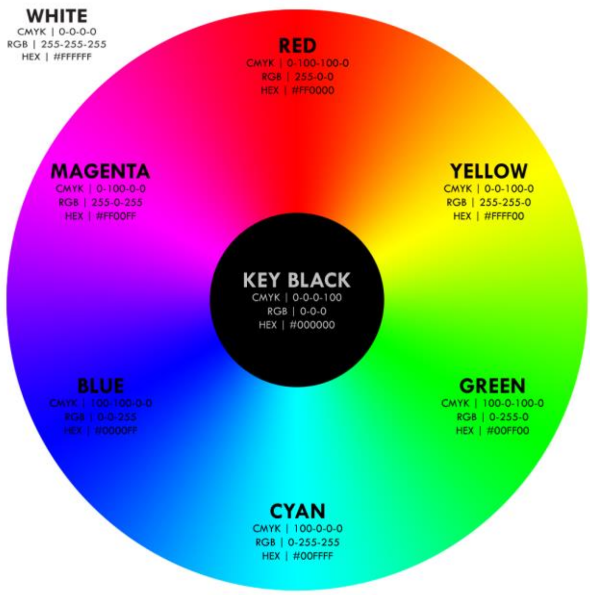



**Figure 12:** The CMYK color wheel.

## 2.3 HSV

The HSV color space was invented by Alvy Ray Smith in 1978. It encodes a color using three components: Hue, Saturation, and Intensity (Value).

The Hue component can be though of as the actual color of the object. In this model, hue is an angle from 0 degrees to 360 degrees.

Saturation is a measure of purity. Saturation indicates the range of grey in the color space. It ranges from 0 to 100%. Sometimes the value is calculated from 0 to 1. When the value is '0,' the color is grey and when the value is '1,' the color is a primary color.

Intensity, which is also referred more accurately as value tells us how light the color is. It is the brightness of the color and varies with color saturation. Actually, this color space is also called HSB, where B attends for brightness. It ranges from 0 to 100%. When the value is '0' the color space will be totally black. With the increase in the value, the color space brightness up and shows various colors.

One advantage of HSV color space with respect to other color spaces such as RGB is that it is quite similar to the way in which humans perceive color.

The HSV color space is usually represented by a cone, as the one in Figure 13.

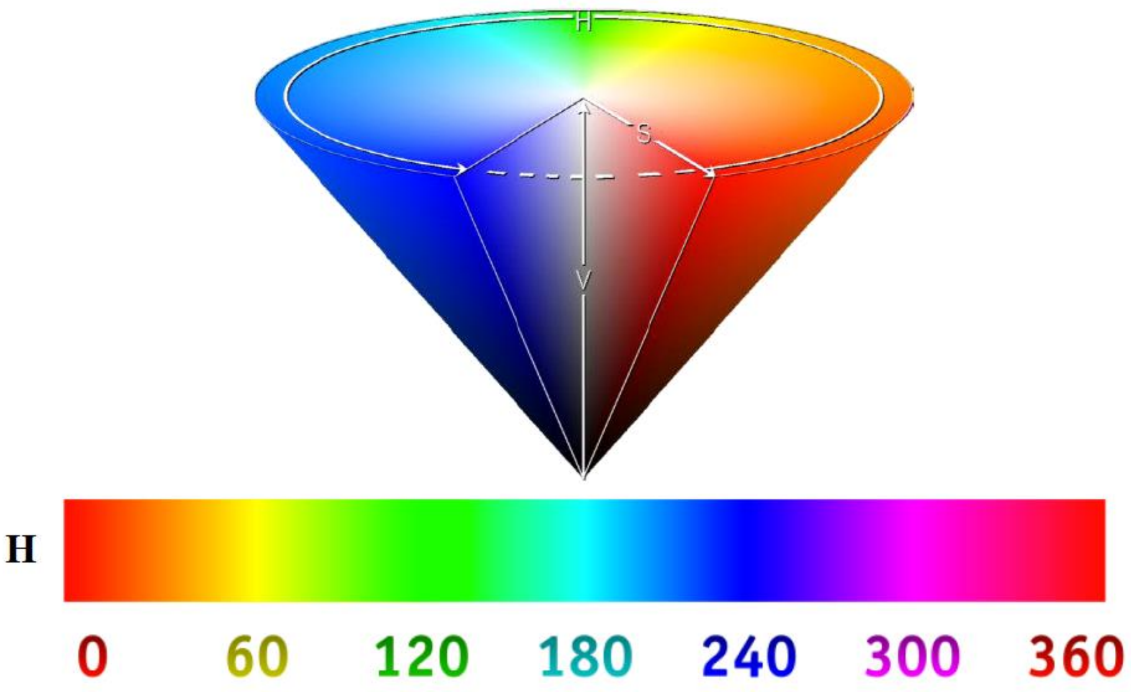



**Figure 13:** The HSV color cone.

## 2.4 HSL

HSL - Hue, Saturation, Lightness. H is the same as in HSV but L and V are defined differently. S is similar for dark colors but quite different for light colors. Also called HLS. In this case, saturation is 0.5 when the color is pure.

## 2.5 CIE

In 1931, the *Commission Internationale de l'Éclairage* (CIE) standardized a set of primaries and color matching functions that are the basis for most color measurement instruments used today. They transformed a set of color matching functions measured by Stiles and Burch to create a set of curves that were more convenient to use. This set is positive throughout the entire visible spectrum, and one of the curves can be used to compute the perceived brightness of the measured color. The CIE standard tristimulus values are notated X, Y and Z. They are often reduced to two dimensions by projecting them onto the X+Y+Z=1 plane, creating the CIE chromaticity diagram with its corresponding chromaticity coordinates, x and y (see Figure 14).

Since the human eye has three types of color sensors that respond to different ranges of wavelengths, a full plot of all visible colors is a three-dimensional figure. However, the concept of color can be divided into two parts: brightness and chromaticity. For example, the color white is a bright color, while the color grey is considered to be a less bright version of that same white. In other words, the chromaticity of white and grey are the same while their brightness differs.

The CIE XYZ color space was deliberately designed so that the Y parameter was a measure of the brightness or luminance of a color. The chromaticity of a color was then specified by the two derived parameters x and y, two of the three normalized values which are functions of all three tristimulus values X, Y, and Z.

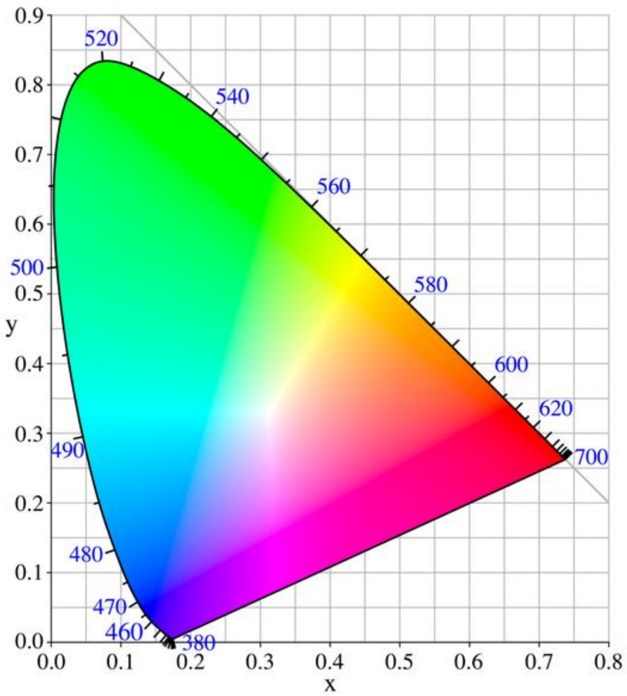



**Figure 14:** The CIE 1931 color space chromacity diagram. The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers. Note that the image itself describes colors using sRGB, and colors outside the sRGB gamut cannot be displayed properly.

The colors accessible to a given display-device are known as its gamut. In Figure 15 we show the colors that will be displayed accurately on a PC with an sRGB-compliant monitor with white point set to 6500K whose brightness and contrast controls are properly set, assuming no (non-standard) system gamma control is in force. Colors outside the triangle are said to be out-of-gamut for display screens. Therefore, these cannot be reproduced on normal display screens (or even recorded in many common image file-formats).

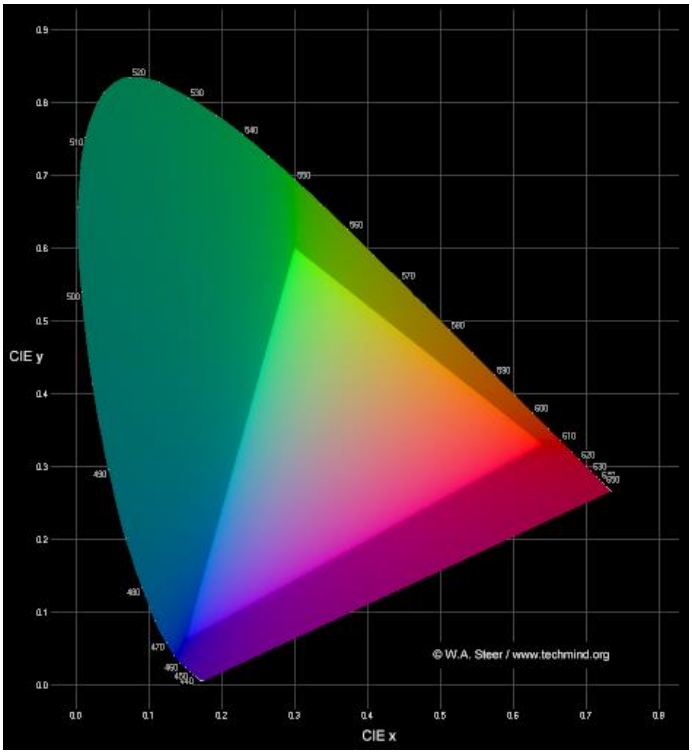



**Figure 15:** The CIE 1931 color space chromacity diagram with a triangle indicating the color gamut for regular monitors

## 3 Color Perception and Color Design

### 3.1 Introduction

The perception of colors is depends on many factors. In particular, the final appearance of colors depends is a combination of perceptual and cognitive effects. Perceptual effects are generated by the processing in the brain of the original retinal signals. Cognitive effects are based on our knowledge of how objects and lights behave in the world.

Obviously, humans do not describe colors in terms of red, green, and blue contributions. People usually describes colors in terms of a hue, such as red, purple, orange or pink. Then, we further describe the color as being light or dark, vivid, and so on… Color spaces that imitate this perceptual organization are said to be more "intuitive".

CIE is not totally uniform color space, since two neighboring colors may not be at the same perceptually perceived distance. However, there are two uniform color spaces defined by the CIE for the measurement of color differences: CIELAB and CIELUV. They are non-linear transformations of the CIE tristimulus values. They have been defined such that a unit step in the space is considered a "just noticeable difference" or JND.

Apart from color, size or spatial frequency have also a strong impact on the perception of a color. For instance, the higher the spatial frequency the less saturated the color. *Chromatic adaptation* describes the visual system's ability to adapt to the color of the light illuminating the scene. Most color is created by shining light off of objects. While the reflected spectrum can be measured with colorimetric instruments, changing the light will change the measured color, sometimes dramatically. But, as we view the world, we do not generally perceive objects changing color as the light shifts. It is similar to an automatic *white-balancing* function for the visual system. That is, the gain controls for the three cones are adjusted separately. Modelling chromatic adaptation is very important for the accurate reproduction of images.

These and other effects affect how users perceive interfaces. For instance, forms with a lot of black separating lines may appear much more cluttered than if such lines are removed.

## 3.2 Color blindness

When dealing with color in interface design, we must take into account color vision deficiencies. Some people are unable to perceive differences between some of the colors that non-colored impaired users can distinguish. These problems are usually caused because one type of cone in the retina is either missing or weak. The most common problems are anomalies in the red-green opponent channel, where either the ability to see red or to see green is impaired. This type of deficiency is called color blindness.

Red-green problems appear in approximately 5 to 10% of men. A much smaller percentage (1-2%) are weaknesses in the blue-yellow channel. There are very few people actually "color blind," or unable to see any hues at all. While most color vision problems are genetic, they can also appear as a side-effect of medication or illness. On the other side, women are less affected by this deficiency, as it only affects less than 1% of females.

## 3.3 Detection

Color blindness is relatively easy to detect. There are some tests such as the Ishihara test that can even be carried out in a computer screen. The Ishihara Color Test was named after its designer, Dr. Shinobu Ishihara, a professor at the University of Tokyo, who first published his tests in 1917.

The test consists of a number of colored plates, called Ishihara plates, each of which contains a circle of dots appearing randomized in color and size. Within the pattern are dots that form a number visible to those with normal color vision and invisible, or difficult to see, for those with a red-green color vision defect. The full test consists of 38 plates, but the existence of a deficiency is usually clear after a few plates, and most tests you will find will show only 6 or 8 color plates. Testing the first 24 plates gives a more accurate diagnosis of the severity of the color vision defect.

The most typical images you find for the tests are:

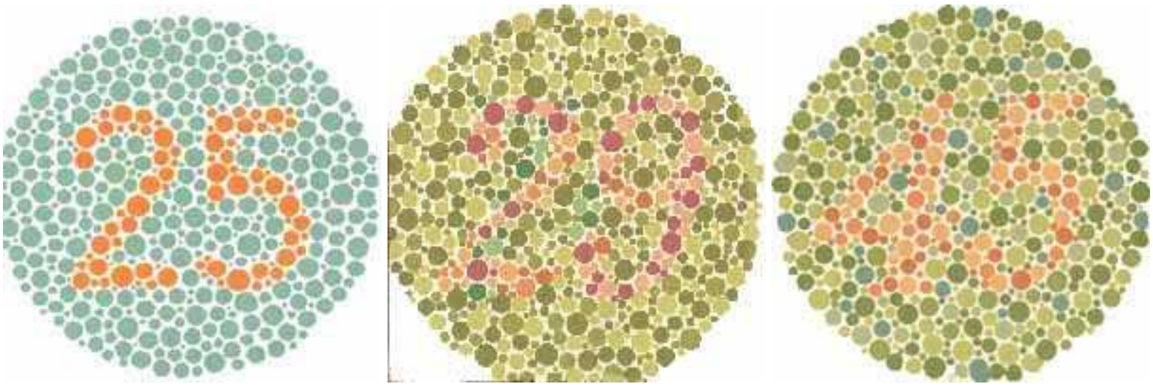


**Figure 16:** Most of the observers should see the numbers 25, 29, and 45, respectively. However, a person with red-green color blindess will only see spots on the center and right images.

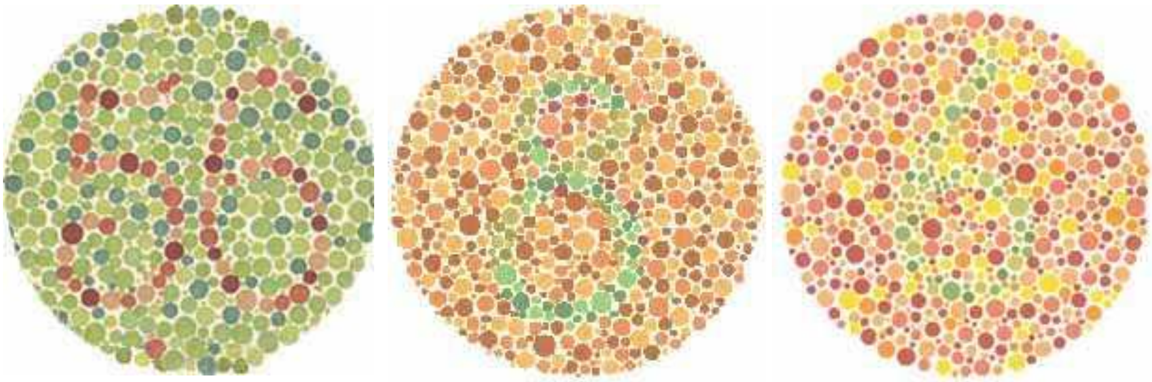


**Figure 17:** The numbers shown here are 56, 8, and 6. A person with red-green color blindness should see the two rightmost numbers incorrectly.

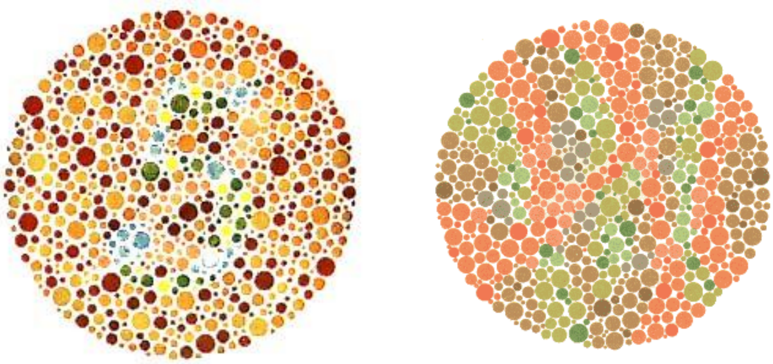


**Figure 18:** A person without color blindness should see the number 5 in left, and no number for the right image. A person with red-green color blindness would see the number 2 in between spots in left figure, while color blind people would see a 5.

### 3.4 Color Friendly Design

There are many benefits designing taking into account color deficiencies. A Web site, for instance, apart from being more accessible, it may also get better ranking in search engines.

If we take into account that color blindness could involve up to 1 in 20 users, if the GUI we design is for a large group of people, discarding an appropriate color design may leave many users apart.

Although it is not simple to design for color blindness because it is difficult to determine what color-blind users see and there are different deficiencies, we may take some safe paths. There is a lot of literature on color design for color-blind people. In Figure 19 you can see the difference of an effective design (top) and an improvable design.

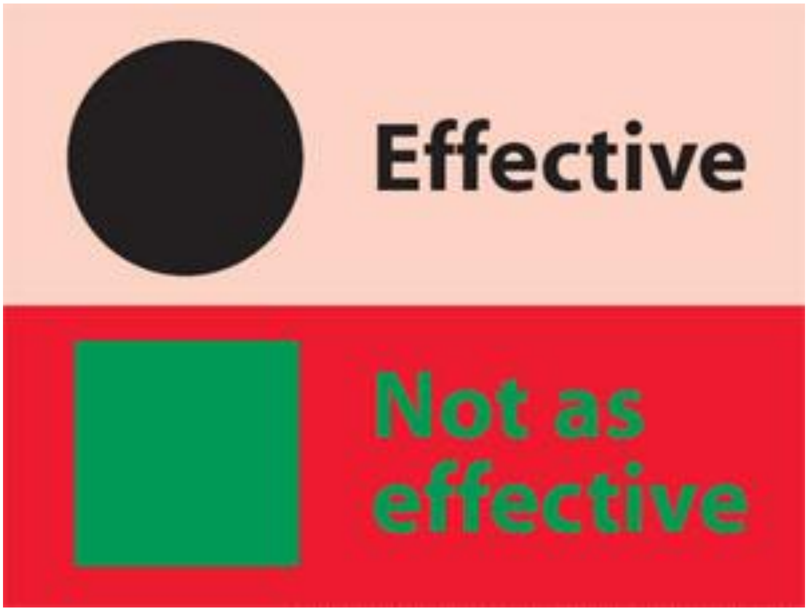



**Figure 19:** Two different designs using color-blind friendly colors (top) and not so friendly colors (bottom).

Some advices for a proper color design are:

- Exaggerate lightness differences between foreground and background colors, and avoid using colors of similar lightness adjacent to one another, even if they differ in saturation or hue.
- Contrast dark colors against light colors (see Figure 20). Use colors placed at distance in the color circle.
- Content areas should be monochromatic with the font color and background at the opposite ends of the color saturation poles (i.e., black text on a white background).
- If we have elements of navigation such as menus, headers and sub-headers, they must have some extra visual enhancement since users seldom devote long periods of time to such elements.


**Figure 20:** Color wheel properly orientated to show light colors (top) and dark colors (bottom).

Contrasting colors or colors on the opposite ends of the color spectrum usually work best for color-blind users (e.g., white and black is the best example). Widgets should have more than one cue: images, buttons, and other elements should be enhanced with an image, shape or text.

Each element should have more than one cue. Images, links, buttons, and other similar elements should be enhanced with an image, shape, positioning or text. For example, a link should be highlighted by color as well as underlined. Take away the color treatment and the underline will let visitors with color blindness know that it is a link.

## 3.5 Harmonic colors

Not all color combinations work well together. You have probably found several times that a certain interface had some colors that "did not get on well together". Some color schemes are better than others, and they communicate a certain *mood*. Based on the reaction you expect from the user, you have to design using a certain color scheme or another.

That a combination of colors works well together does not mean that you can use them for text and background, on the contrary, they may provide poor contrast. Black text over white background is the best for text-heavy designs, while white text over black goes slightly after.

One needs not to be a skilled painter or a fashion victim to be able to combine colors with success. Actually, there are several easy techniques that mostly ensure harmonic color combinations that will ensure a pleasant look. The mood is up to you, but at least, it is quite easy to find color schemes that work. Otherwise, many websites such as Paletton (http://paletton.com/) can help you get a color scheme for your application or web.

### 3.5.1 Color wheels

The first color wheel was designed by Sir Isaac Newton in 1666. Color wheels are used to help understand the color harmonies (what works, what doesn't, and what the colors communicate). The color wheel consists of three primary colors (red, yellow, blue), three secondary colors (colors created when primary colors are mixed: green, orange, purple) and six tertiary colors (colors made from primary and secondary colors, such as blue-green or red-violet), as illustrated in Figure 21.


**Figure 21:** The **primary** (red, yellow, blue), **secondary colors** (green, orange, purple) and **tertiary colors** (colors made from primary and secondary colors).

We can use color wheels to select colors for our designs that are harmonic (that is, do not crash with each other). There are several strategies to do this, as described next.

### 3.5.2 Complementary colors

Complementary colors are the ones that are opposite each other on the color wheel, for example red and green. The high contrast of complementary colors creates a vibrant look especially when used at full saturation. This color scheme must be managed well so it is not jarring. Complementary colors are tricky to use in large doses, but work well when you want something to stand out. They are really bad for text.

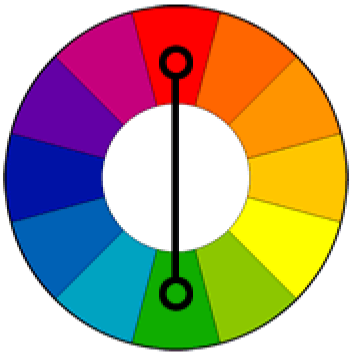


**Figure 22:** Complementary colors.

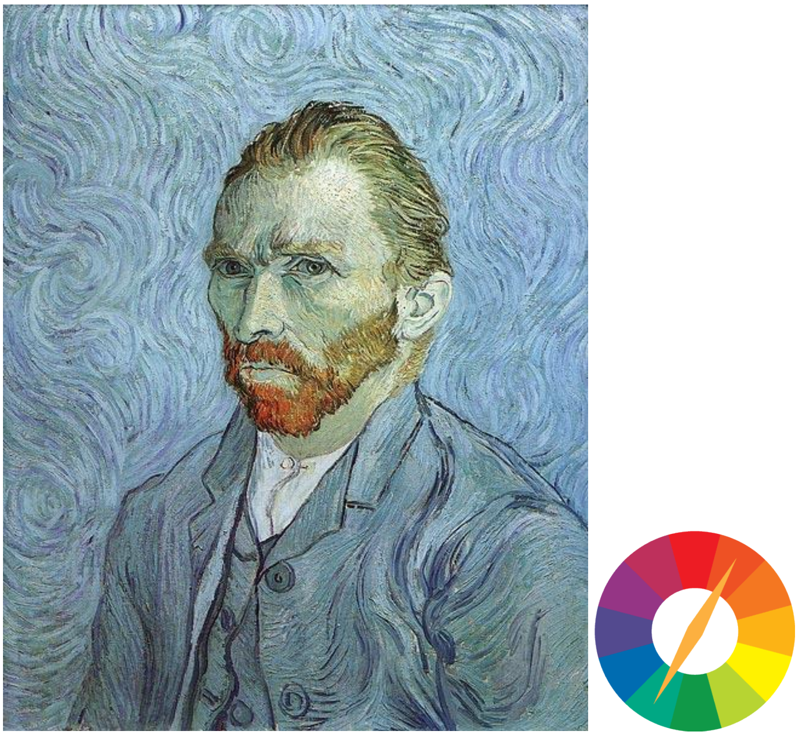


**Figure 23:** Complementary colors used in *Self portrait*, 1889, by Vincent Van Gogh.

### 3.5.3 Split-complementary colors

A split complementary color scheme is a variation of the complementary scheme but instead of just two colors directly opposite on the color wheel, two of the three colors are adjacent to one of the colors that is opposite. You can choose one color, and the two adjacent ones to the opposite of the first color. This color scheme has the same strong visual contrast as the complementary color scheme, but has less tension.

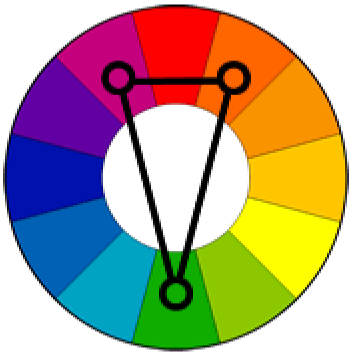


**Figure 24:** Split-complementary colors.


**Figure 25:** Split-complementary colors used in *Two Eggplants*, by Chris Carter.

### 3.5.4 Triadic colors

A triadic color scheme uses colors that are evenly spaced around the color wheel. Triadic color harmonies tend to be quite vibrant, even if you use pale or unsaturated versions of your hues. To use a triadic harmony successfully, the colors should be carefully balanced - let one color dominate and use the two others for accent. Any three colors equidistant around the color wheel form a triad and can be used in this color scheme. You can use semi-neutral colors that mix colors of the triad, and also add black and white.

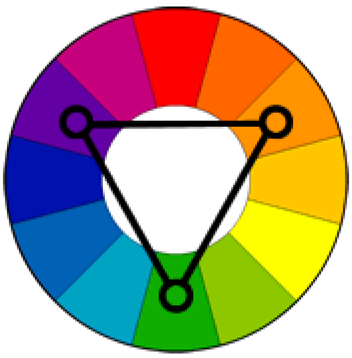


**Figure 26:** Triadic color scheme.

**Figure 27:** The famous *Marilyn Monroe* by Andy Warhol is a good example of triadic color selection.

Not only painters use the color schemes sagely, but also labels know how to use them. Figure 28 shows the Burger King logo, that also uses a triadic color combination.


**Figure 28:** Burber King also uses a color triad.

### 3.5.5 Analogous colors

An analogous color scheme is any three adjacent primary, secondary, or tertiary colors on the color wheel. They usually match well and create serene and comfortable designs. These schemes can be warm or cool. Each can be neutralized by use of its complement, and black and white can be used. It is important to ensure that you have enough contrast. Typically, one color is the dominant, and the second is the support. Then, the third is used as accent.

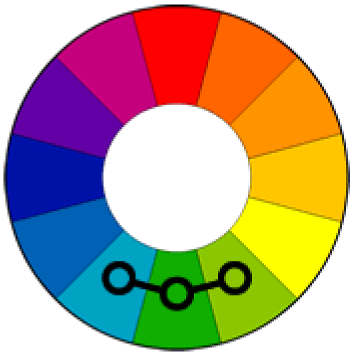


**Figure 29:** Analogous colors.

**Figure 30:** The *Byciclist* by Deane Nettles uses an analogous color scheme.

### 3.5.6 Tetradic color scheme

A tetradic color scheme is one using four or more colors on the color wheel (eg., green, violet, red and yellow). This rich color scheme offers plenty of possibilities for variation. The tetradic color scheme works best if you let one color be dominant. You should also pay attention to the balance between warm and cool colors in your design.

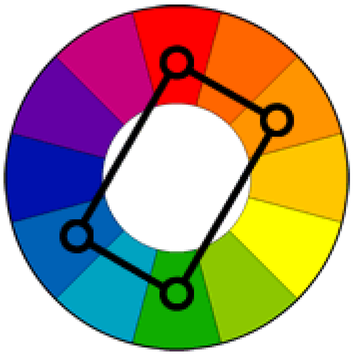


**Figure 31:** Tetradic color scheme.


**Figure 32:** Tetradic color scheme in use in the painting *Family treasures number 29, Googles and Wooden Circle Stamp*, by Chris Carter.

The square color scheme is similar to the rectangle, but with all four colors spaced evenly around the color circle. The square color scheme works best if you let one color be dominant.