IDI - Visual Design - Color

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Contents

1 Colour

1.1 Introduction

Light enters the eye as spectrum of colours, 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 colour reproduction technologies. Instead of reproducing the spectral stimulus, they create an equivalent response, or metameric match by mixing primary colours in a controlled way.

Trichromacy and metamerism can also be applied to the problem of measuring colour. It is important in many industries to be able to measure coloured 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 colours 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 colour measurement is much older, and is based on experiments involving matching colours with sets of three primary lights. This is called colorimetery.

1.2 Colorimetery

The colour 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 colours such as the monochromatic colours of the spectrum, or those generated by filtering a white light. For any set of three independent primaries, you can match any other colour. 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 colour based on three primary lights. Any colour 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 colour.

How do we know what primary values match a particular colour? Clearly we cannot perform the colour matching experiment on all possible spectra. The answer is to use the fact that coloured 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 coloured 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 colour, we use Grasman's law to construct a set of colour matching functions for the primaries. We perform the colour matching experiment on each of the monochromatic spectral colours (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 colour 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.

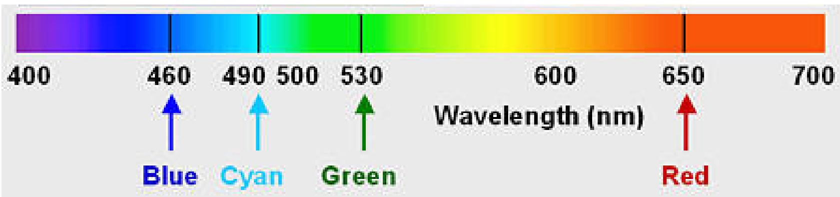
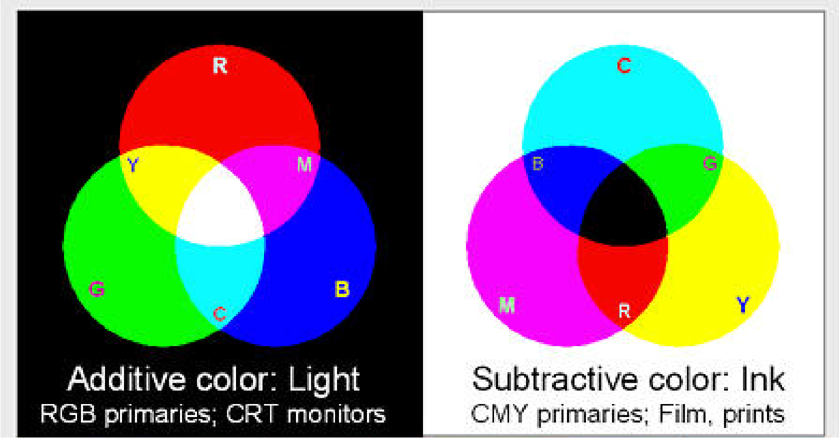


Figure 9: Visible light spectrum.

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 colour-sensitive light receptors called cones, which respond roughly to red, blue and green light (around 650, 530 and 460 nm, respectively). A range of colours can be reproduced by one of two complimentary approaches (also shown in Figure 10):

- **Additive colour:** Additive colour 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 colour 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 colour:** Subtractive colour systems filter the red, green and blue components of the image from white light. To do this, they use coloured 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 colour systems is that they use a single, white light source instead of three coloured ones. Furthermore, for reflection prints, this light is simply the light in the room.

Figure 10: Additive and subtractive colours.

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 colour is highly device dependent. There are many algorithms for converting RGB to CMYK. Photographic editing should be done in RGB (or related) colour spaces. Conversion to CMYK (usually with colours added to extend the printer colour gamut) should be left to the printer driver software.

You can obtain a wide range of colours, but not all the colours the eye can see, by combining RGB light. The gamut of colours 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 Colour Depth

When we represent a colour, 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 colour **depth** and it is actually 24 bits per pixel. Initially, computer screens had only a single bit per pixel, and therefore only two colours were representable.

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

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

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

2 Colour models

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

2.1 RGB

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

In the RGB colour model, colours 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 colour would be R=255 G=0 B=255. Black would be R=0 G=0 B=0 (a total absence of light).

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

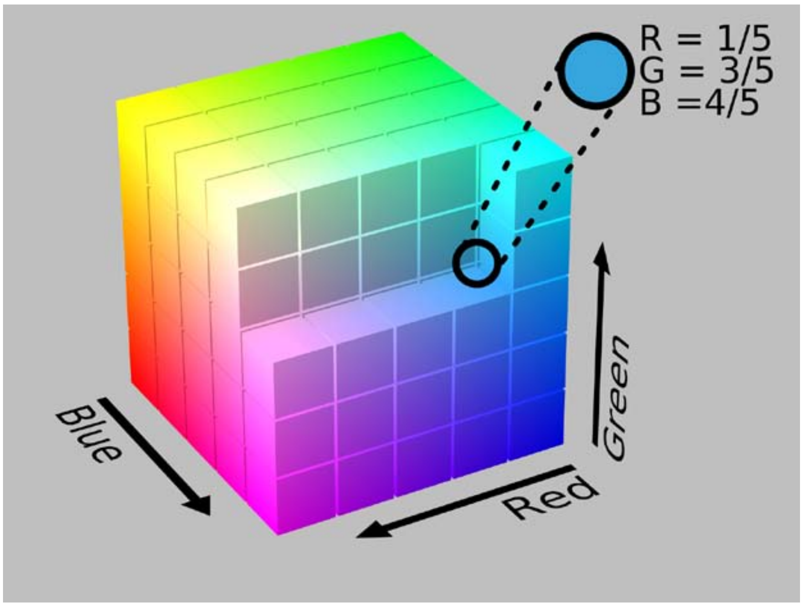


Figure 11: The RGB colour cube.

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

2.2 CMY(K)

CMYK is a subtractive colour model used in colour printing. The CMYK printing method is also known as "four-colour process" or simply "process" colour. All of the colours in the printable portion of the colour 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 colour. When various tints of the four colours 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 colouring the print.

The CMYK model forms its gamut from the primary subtractive colours 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 colour. Black ink is added to this system to compensate for these impurities.

In the CMYK colour model, colours 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 colour wheel in Figure 12.

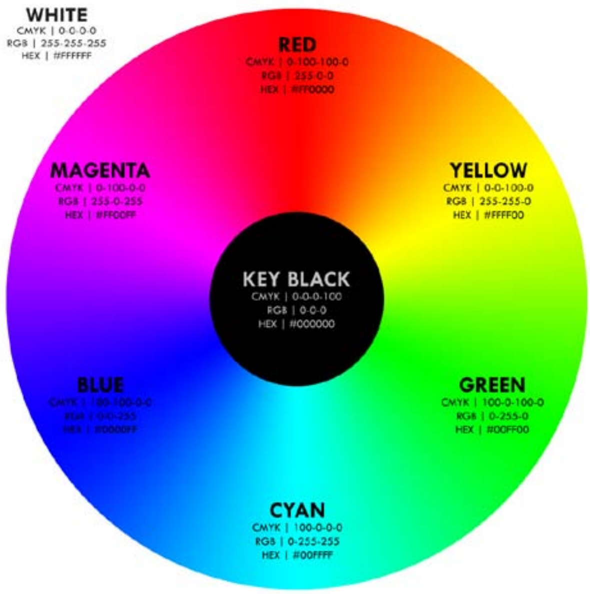


Figure 12: The CMYK colour wheel.

2.3 HSV

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

The Hue component can be though of as the actual colour 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 colour space. It ranges from 0 to 100%. Sometimes the value is calculated from 0 to 1. When the value is '0,' the colour is grey and when the value is '1,' the colour is a primary colour.

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

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

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

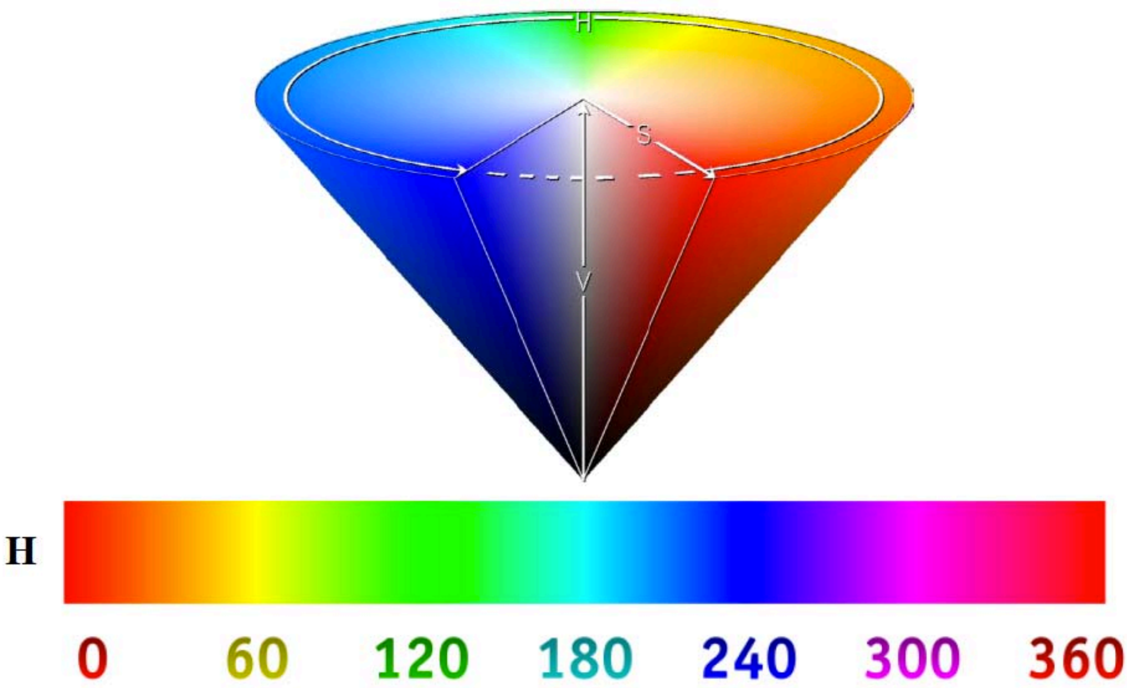


Figure 13: The HSV colour cone.

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 colours but quite different for light colours. Also called HLS. In this case, saturation is 0.5 when the colour is pure.

2.5 CIE

In 1931, the *Commission Internationale de l'Éclairage* (CIE) standardized a set of primaries and colour matching functions that are the basis for most colour measurement instruments used today. They transformed a set of colour 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 colour. 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 colour sensors that respond to different ranges of wavelengths, a full plot of all visible colours is a three-dimensional figure. However, the concept of colour can be divided into two parts: brightness and chromaticity. For example, the colour white is a bright colour, while the colour 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 colour space was deliberately designed so that the Y parameter was a measure of the brightness or luminance of a colour. The chromaticity of a colour 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.

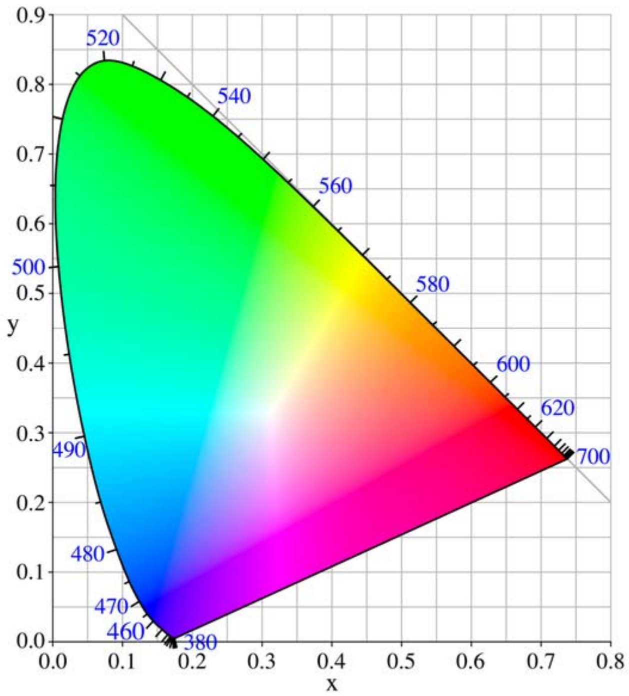


Figure 14: The CIE 1931 color space chromacity diagram. The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers. Note that the image itself describes colors using sRGB, and colors outside the sRGB gamut cannot be displayed properly.

The colours accessible to a given display-device are known as its gamut. In Figure 15 we show the colours 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. Colours 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).

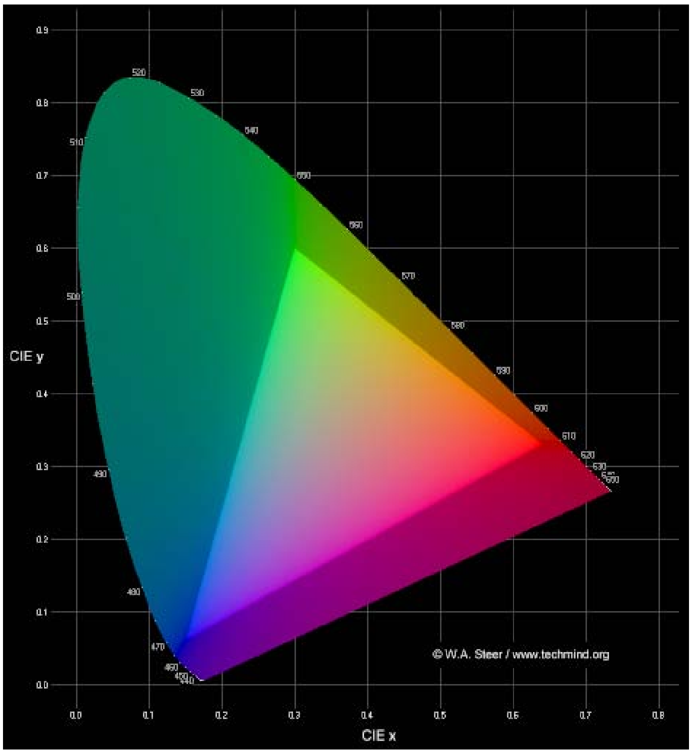


Figure 15: The CIE 1931 colour space chromacity diagram with a triangle indicating the colour gamut for regular monitors

3 Colour conversions

For many applications, it may be useful to transform from a colour space to another. Usually, these transformations have problems, because the colour spaces do not completely match. As a consequence, there are sometimes colours that we may not obtain, or multiple colours that will fall to the same colour in another space. This problem is inherent to the colour space definitions and we cannot avoid it.

For CMY and CMYK colour spaces, we have another added problem: the colours that we are trying to generate may be not reproducible since our printing devices may have limitations, as well as the screens we use to define the desired colour.

3.1 RGB to CMY and CMYK

Transformation between RGB and CMY or CMYK spaces is pretty simple:

```
C = 1-R;
M = 1-G;
Y = 1-B;
```

If we want to use black, the transformation from RGB to CMYK, with a percentage *s* of black is as follows:

```
K = min(1-r,1-g,1-b)*s/100;
C = 1-r-K;
M = 1-g-K;
Y = 1-b-K;
```

3.2 CMY and CMYK to RGB

The inverse transformations are straightforward. From CMY to RGB:

```
R = 1-c;
G = 1-m;
B = 1-y;
```

CMYK to RGB:

```
R := max(1-c-k,0);
G := max(1-m-k,0);
B := max(1-y-k,0);
```

3.3 RGB to HSV

You can find code for transformations between RGB and HSV in the CD of the VIG course. Here we show a scheme of the algorithm:

```
max = maximum of RGB
min = minimum of RGB

V = max
S = (max - min) / max

if S = 0, H is undefined, else
  delta = max-min

  if R = max, H = (G-b)/delta
  if G = max, H = 2 + (B-R)/delta
  if B = max, H = 4 + (R-G)/delta

  H = H*60
  if H < 0, H = H + 360
```

3.4 HSV to RGB

The transformation from HSV to RGB is as follows:

```
if S = 0 and H = undefined, R = G = B = V

if H = 360, H = 0
H = H / 60
i = floor(H)
f = H - i
p = V*(1-S)
q = V*(1-(S*f))
t = V*(1 - (S * (1-f)))

if i = 0, R = v, G = t, B = p
if i = 1, R = q, G = v, B = p
if i = 2, R = p, G = v, B = t
if i = 3, R = p, G = q, B = v
if i = 4, R = t, G = p, B = v
if i = 5, R = v, G = p, B = q
```

where *floor* is the C *floor* function

3.5 CIE XYZ to RGB

To transform from XYZ to RGB we use a matrix, as shown in the following matrix transformation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.240479 & -1.537150 & -0.498535 \\ -0.969256 & 1.875992 & 0.041556 \\ 0.055648 & -0.204043 & 1.057311 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

The range for valid R, G, B values is [0,1]. Note that this matrix has negative coefficients. Some XYZ colour may be transformed to RGB values that are negative or greater than one. This means that not all visible colours can be produced using the RGB system.

3.6 RGB to CIE XYZ

The inverse from RGB to XYZ transformation matrix is as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

4 Colour Perception and Colour Design

4.1 Introduction

The perception of colours is depends on many factors. In particular, the final appearance of colours 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 colours in terms of red, green, and blue contributions. People usually describes colours en terms of a hue, such as red, purple, orange or pink. Then, we further describe the colour as being light or dark, vivid, and so on… Colour spaces that imitate this perceptual organization are said to be more “intuitive”.

CIE is not totally uniform colour space, since two neighbouring colours may not be at the same perceptually perceived distance. However, there are two uniform colour spaces defined by the CIE for the measurement of colour 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 colour, size or spatial frequency have also a strong impact on the perception of a colour. For instance, the higher the spatial frequency the less saturated the colour. *Chromatic adaptation* describes the visual system’s ability to adapt to the colour of the light illuminating the scene. Most colour 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 colour, sometimes dramatically. But, as we view the world, we do not generally perceive objects changing colour 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.

4.2 Colour blindness

When dealing with colour in interface design, we must take into account colour vision deficiencies. Some people are unable to perceive differences between some of the colours that non-coloured 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 colour 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 "colour blind," or unable to see any hues at all. While most colour 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.

4.3 Detection

Colour 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 Colour 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 coloured plates, called Ishihara plates, each of which contains a circle of dots appearing randomized in colour and size. Within the pattern are dots that form a number visible to those with normal colour vision and invisible, or difficult to see, for those with a red-green colour 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 colour plates. Testing the first 24 plates gives a more accurate diagnosis of the severity of the colour vision defect.

The most typical images you find for the tests are:

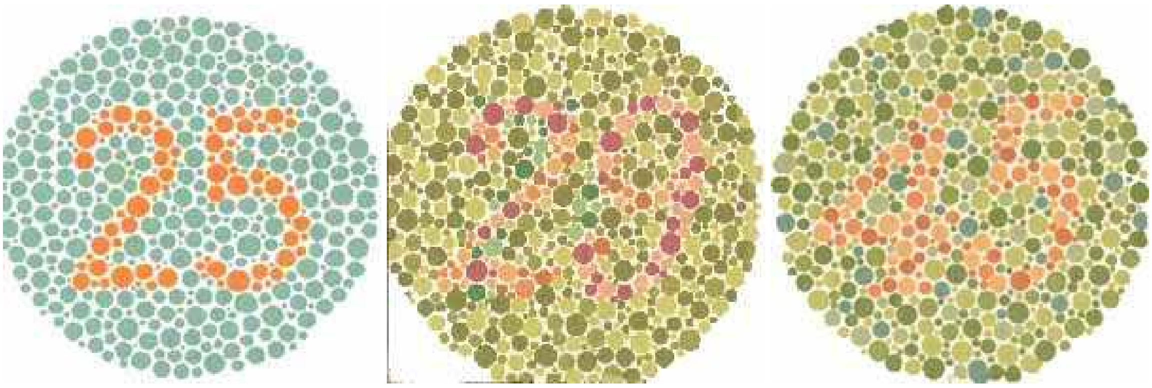
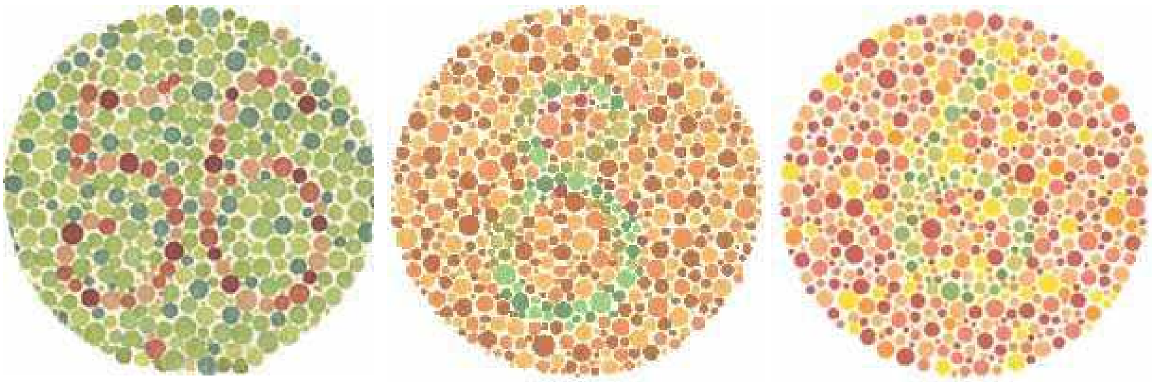
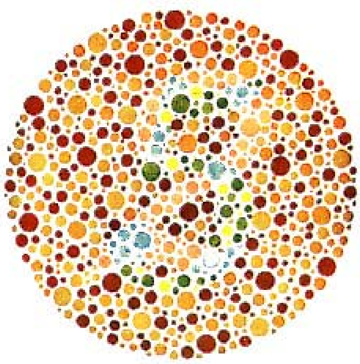


Figure 16: Most of the observers should see the numbers 25, 29, and 45, respectively. However, a person with red-green colour blindess will only see spots on the center and



right images.

Figure 17: The numbers shown here are 56, 8, and 6. A person with red-green colour



blindness should see the two rightmost numbers incorrectly.

Figure 18: A person without colour blindness should see the number 5. A person with red-green colour blindness would see the number 2 in between spots.

4.4 Colour Friendly Design

There are many benefits designing taking into account colour 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 colour blindness could involve up to 1 in 20 users, if the GUI we design is for a large group of people, discarding an appropriate colour design may leave many users apart.

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

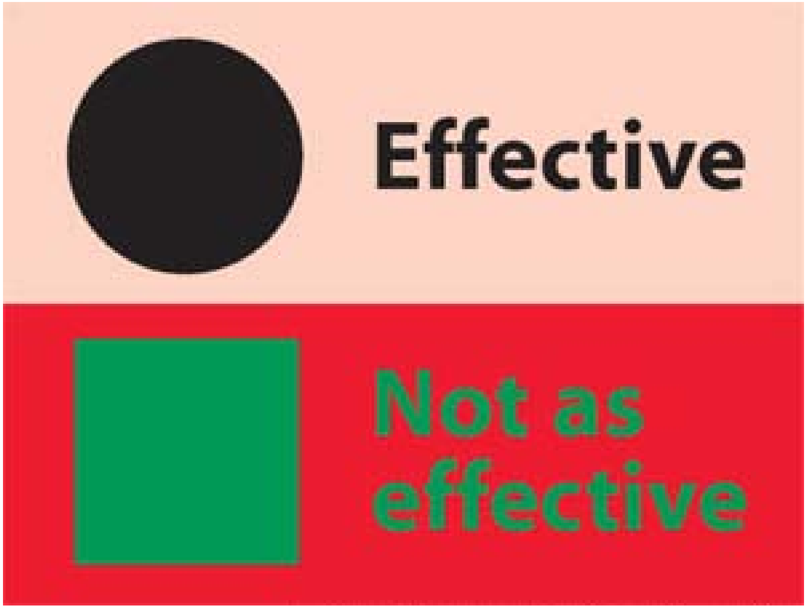


Figure 19: Two different designs using colour-blind friendly colours (top) and not so friendly colours (bottom).

Some advices for a proper colour design are:

- Exaggerate lightness differences between foreground and background colours, and avoid using colours of similar lightness adjacent to one another, even if they differ in saturation or hue.
- Contrast dark colours against light colours (see Figure 20). Use colours placed at distance in the colour circle.
- Content areas should be monochromatic with the font colour and background at the opposite ends of the colour 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: Colour wheel properly orientated to show light colours (top) and dark colours (bottom).

Contrasting colours or colours on the opposite ends of the colour spectrum usually work best for colour-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 colour as well as underlined. Take away the colour treatment and the underline will let visitors with colour blindness know that it is a link.