True Colour Theory

an introductory treatise on

Basic Colour Concepts

Rudolf L. van Renesse[1]

INTRODUCTION

I prepared this paper in 1996 as a reaction on quite a few web pages that present a more or less erroneous treatment on colour theory. The most frequent error that I encountered is, that the subtractive primaries are denoted as red, yellow and blue. This is an unfortunate and nearly ineradicable notion that has historical grounds, which are explained below. Furthermore, red and green are often misrepresented as complementary colours and as a result fancy and distorted colour wheels are sometimes concocted. Finally, the relation between subtractive and additive colour mixing often remains confused, if mentioned at all.
As a result of all this, and contrary to what is intended by these sincere contributions, the layperson is presented with ideas that do not agree with observed facts and thus do not provide a clear outline of colour theory.

This paper on **True Colour Theory** intends to set a few things straight. Colour theory is shown to involve a consistent set of lucid laws, verifiable by elementary experiments. I will present a little bit of historical background together with theory and practice.
I trust the following will disentangle at least some the chaos.

[1]VanRenesse Consulting: info@vanrenesse-consulting.com; http://www.vanrenesse-consulting.com/

1. WHAT ARE PRIMARY COLOURS?

Practice teaches that the mixing of various colours invariably results in new colours. Depending on the starting-colours and their number and mutual proportions, a seemingly infinite series of new hues, shades and tints can be created. This creative play of marrying colours seems an infinite, until it appears that certain laws govern this delightful play. However extensive the number of colours may be that can be created by mixing others, some colours never appear to be obtainable in this manner. And exactly these unruly colours, if applied as starting-colours, seem to yield the largest range of new mixed colours. The inevitable question arises which law underlies the phenomena observed.

The question leads to the formulation of one of the most elementary problems in colour theory: how can a maximum number of hues, shades and tints be made to result from the mixing, in various proportions, of a minimum number of available starting-colours, the so called **primary colours**.

This minimum number of starting colours appears to be three. The largest colour gamut is obtained by mixing these three primaries in various proportions. Which these primary colours are, appears to depend on the type of colour mixing applied.

Two basic types of colour mixing exist:
The absorptive mixing of coloured tinctures, paints and pigments, generally called **subtractive colour mixing** and the **additive colour mixing** of coloured lights. These colour mixing systems are briefly discussed below.

The definition of primary colours, originally defined by the German astronomer and cartographer Tobias Mayer (1723-1762), is twofold; a negative and a positive statement [1]:

1. **Primary colours cannot be obtained through mixing other colours.**
   For instance, yellow is a subtractive primary because experience learns that yellow can in no way result from any mixture of other dyes or pigments. And red is an additive primary because it cannot result from any mixture of coloured lights.

2. **From the primary colours all other *types of hue* can be obtained by mixing.**
   For instance the well known subtractive production of green from yellow and cyan blue pigments and the (less well known) additive production of yellow from red and green lights.

This definition of primary colours holds for all subtractive and additive colour-mixing techniques. It should be mentioned that both mixing techniques have a limitation. I have italicised “types of hue” in the second statement, because not all hues can be obtained by mixing primaries. I explain this limitation in my chapter 1, sections 1.3.4 and 1.3.6 of the 3rd edition of my book Optical Document Security.

Obviously, Mayer’s definition is of an empirical nature. Which the primary colours are cannot be deduced from this definition, but only by means of an experimental process of mixing colours by trial and error. Without a more advanced knowledge of the fundamental operation of our organ of sight, this elementary problem cannot be solved a priori. Although this necessary knowledge became available in the course of the second half of the 19th century, the correct conclusions were only drawn in the beginning of the 20th century. And even while our 20th century has expired, misconceptions appear to be abundant.

2. WHAT IS SUBTRACTIVE COLOUR MIXING?

Subtractive (absorptive) colour mixing involves the mixing of pigments, dyes and paints, as well as placing colour filters or glass containers filled with coloured tinctures in series. For instance, if a yellow and a cyan blue paint or tincture are mixed, the result is the same as if a yellow and a cyan blue colour filter are stacked: green.
The term subtractive does not refer to arithmetic subtraction, but rather refers to the fundamental contrast with additive colour mixing, as well as to the fact that the subtractive colour mixture is always darker than either of the constituting colours.

There appear to be three colours that, when mixed in various proportions, offer the largest possible subtractive colour gamut. These are the subtractive primaries:

YELLOW
MAGENTA
CYAN BLUE

This became an established fact in the printing and photographic industry, as well as in the craft of mixing paints and pigments in the beginning of the 20th century.

The secondary colours red, green and blue violet result from mixing two subtractive primaries in proper proportions, while black or at least a dark grey result from mixing proper proportions of all three of them:

YELLOW + ***MAGENTA*** → ***RED***
YELLOW + ***CYAN BLUE*** → ***GREEN***
CYAN BLUE + ***MAGENTA*** → ***BLUE VIOLET***
CYAN BLUE + ***MAGENTA*** + ***YELLOW*** → ***BLACK***

The result of subtractive mixing is always darker than the composing colours. You can try this with watercolours, acrylic paint, coloured pencil, tinctures, etc.
The primary colours are ***not*** red, yellow and blue. By definition red cannot be a subtractive primary colour because it results from the mixing of magenta and yellow. Orange will result from the mixing of a little magenta and excess yellow.
Try to mix the red and blue colours that you thought to be primaries. The result will be something like chestnut and certainly not purple as is often maintained.

This is a subtractive experiment that you also might wish to perform:
Cut 3 disks of yellow, magenta and cyan colour foils, partly overlap these coloured disks and observe them against the light (in transmission) or mount them in a slide and project them on a white screen. Surprise! You will find that the following holds (see Figure 1):

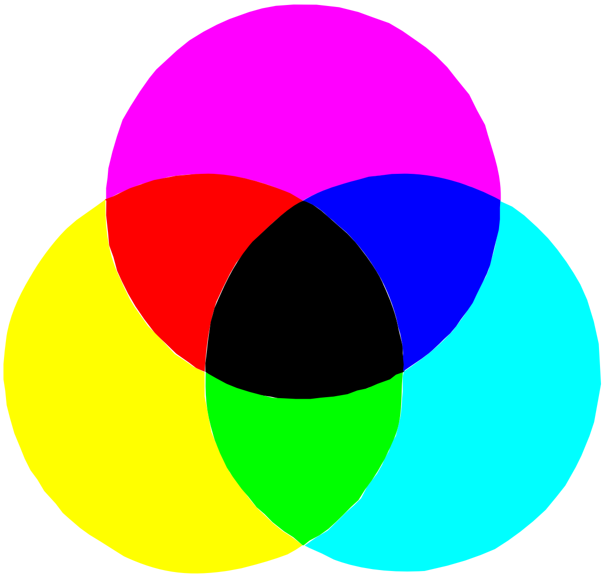
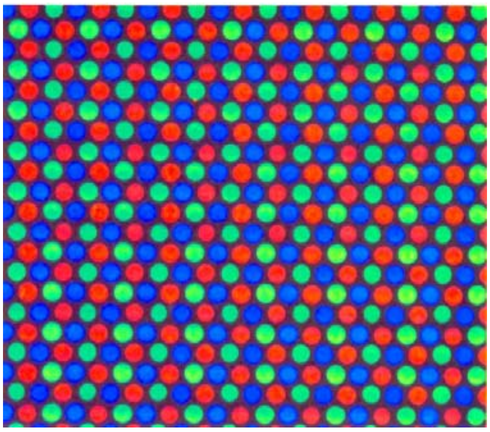


Figure 1 - Subtractive colour mixing of yellow, magenta and cyan by overlapping colour filters: the subtractive secondary colours appear to be red, green and blue violet.

3. WHAT IS ADDITIVE COLOUR MIXING?

Additive colour mixing involves the mixing, or rather overlapping, of beams of coloured light on a white background. In this case the term additive is exact, because the spectral response curve of the mixture can be calculated by adding the energies of the spectral components of the composing beams of light. The result of additive colour mixing is always lighter than either of the composing colours. A well-known variant of additive colour mixing makes use of the limited resolving power of our eye. The colour mixtures are brought about by the combined effect of the tiny phosphorescent colour dots, invisible to the naked eye, that make up our TV and computer screens. The figure on the left shows an enlargement of such a screen. There are three colours that, when mixed in various intensities, offer the largest possible additive colour gamut. These are the additive primaries:



RED
GREEN
BLUE VIOLET

The secondary colours yellow, magenta and cyan blue result from mixing two additive primaries in proper intensities, while white results from mixing proper intensities of all three:

BLUE VIOLET + ***GREEN*** → ***CYAN BLUE***

BLUE VIOLET + ***RED*** → ***MAGENTA***

RED + ***GREEN*** → ***YELLOW***

RED + ***GREEN*** + ***BLUE VIOLET*** → ***WHITE***

These additive results are generally demonstrated by projecting overlapping coloured disks of light on a white screen, from three projectors provided with coloured slides. The result is shown in Figure 2.

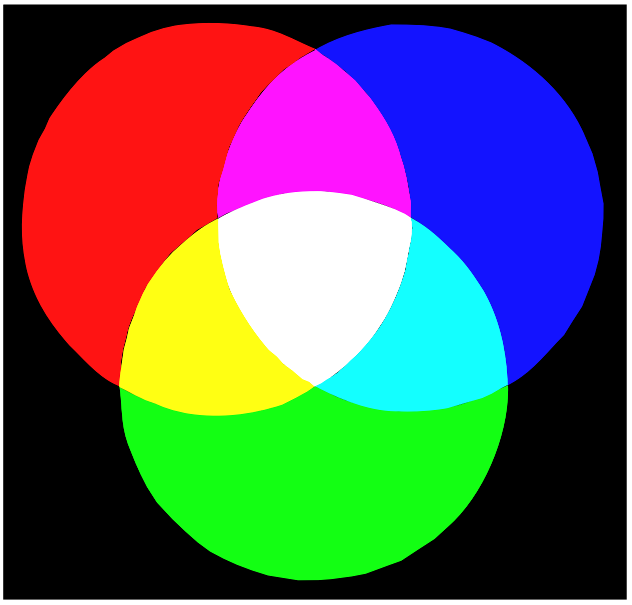


Figure 2 - Additive colour mixing of red, green and blue violet:
The additive secondary colours are yellow magenta and cyan.

Further variants of additive mixing consist of projecting coloured lights, flashing in rapid succession on a screen, or rapidly spinning coloured papers mounted on a disk, the so called Maxwell disk. In these cases the constituting colours are fused into a single colour perception due to our persistence of vision. These types of colour mixing result in the **averaging of colours** rather than in their addition [2]. The result, for instance, of mixing red and green would rather be brown than yellow, while the mixture of red, green and blue violet would appear as a neutral grey rather than white.

conclusion:

It follows from Figure 1 and Figure 2 that subtractive colour mixing and additive colour mixing are complementary processes: the mixing of matter (dyes, pigments) versus the mixing of light. The primary colours of subtractive colour mixing are the secondary colours of additive colour mixing, and vice versa. In fact there are two complementary primary triplets, that can produce each other by colour mixing:

1. Matter	2. Light
YELLOW	*BLUE VIOLET*
MAGENTA	*GREEN*
CYAN	*RED*

4. WHAT ARE COMPLEMENTARY COLOURS?

This question requires an answer on three different levels, the physical level, the physiological level and the psychological level.

1. The physical level

On the *physical level* complementary colours neutralise each other to a colourless result:

- Mixed subtractively, in proper proportion, complementary colours neutralise each other to produce black (or at least a dark grey, depending on ink quality and application technique).
- Mixed additively, in proper proportion, complementary colours neutralise each other to produce white.

This is illustrated in Figure 3.

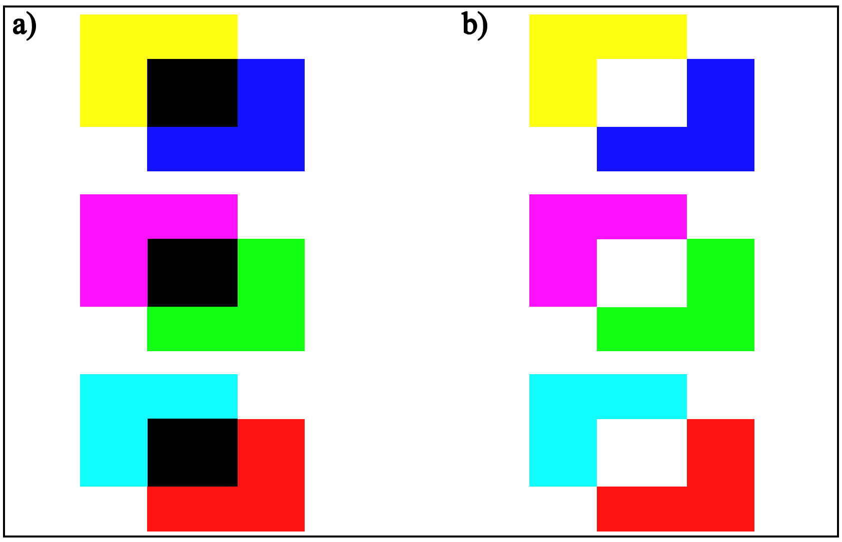


Figure 3 - a) subtractive mixture of complementaries $\rightarrow$ black
b) additive mixture of complementaries $\rightarrow$ white

2. The physiological level

On the *physiological level* complementary colours evoke each other. The most well known evidence of this is presented by the so called *after images*, but the phenomenon of "coloured shadows", which was extensively studied by Johann Wolfgang von Goethe, is also of a physiological nature [3- 5].

In Figure 4 the complementary colours are displayed as neighbours for an after image experiment. Look at the dot within each complementary pair for some 15 - 30 seconds and then look at the adjacent dot at the right. It will appear that, in the after image, the colour hues are left right reversed. This is because yellow evokes blue violet, magenta evokes green, cyan blue evokes red, and vice versa. It must be borne in mind that after image colours appear somewhat less saturated than the colours that evoke them.

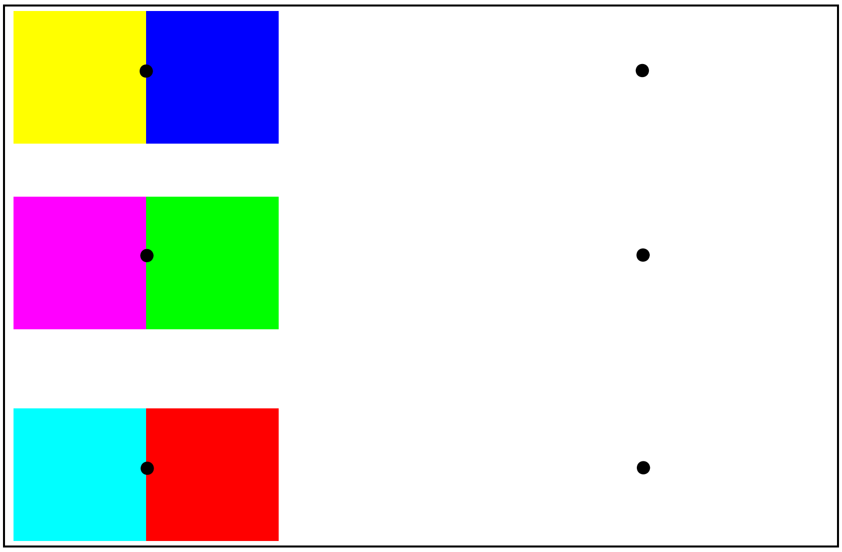


Figure 4 - Swapping colours in after images

3. The psychological level

On the *psychological level* complementary colour evoke contrasting and maximally opposing moods. The warm, passionate and approaching red colours oppose the cool, reserved and receding blues; the light, merry and radiant yellows oppose the sombre, earnest and melancholic blue violets; and the modest, serene greens oppose the proud, majestic purples. According to Goethe, jointly, two opponents create a certain harmonious equilibrium.

Other psychological properties of the contrasting complementaries are:

Yellow:
light, warm

Blue violet:
dark, cool

Magenta:
light, warm as well as cool, majestic

Green:
dark, neither warm nor cool, modest

Cyan blue:
light, cool

Red:
dark, warm.

5. Prismatic colour experiments

In 1791 Goethe carried out a series of beautiful prismatic experiments, which are highly illustrative for the laws of Colour Theory. To repeat his main experiments, it is sufficient to observe colour prints of Figure 5 and Figure 7 through a glass prism, its refracting angle pointing to your right. Observing your screen through a prism will give different effects because the screen white is not continuous, but additively generated by the RGB phosphors. Of course, it is most convenient to replicate Figure 5 and Figure 7 with some black and white

cardboards.
It must further be borne in mind that, not only these two experiments, but many more of Goethe's prismatic experiments are worthwhile of repeating.
Figure 5 presents a simple black and white edge (top) and a white and black edge (bottom). Observed through a prism, the top edge will mainly display the warm colours red and yellow, the bottom edge will mainly display the cool colours cyan blue and blue violet.

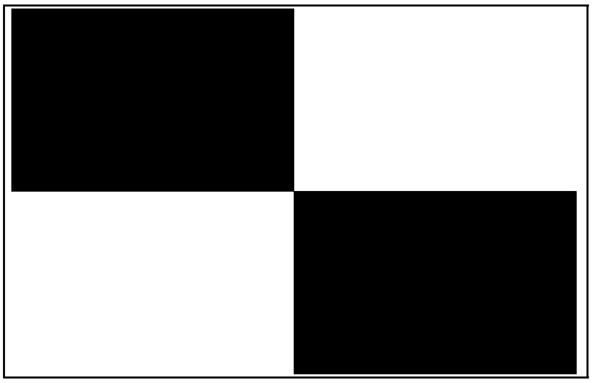


Figure 5 - Observe through a glass prism.

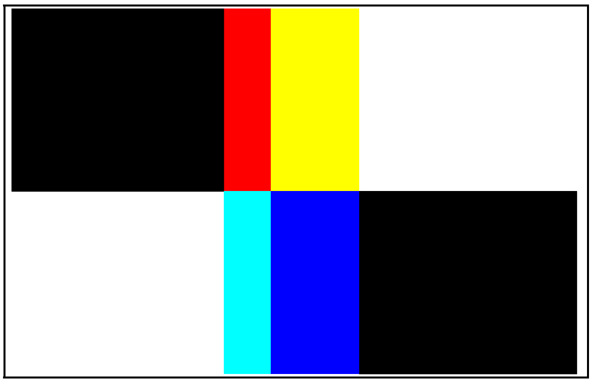


Figure 6 - Figure 5 seen through a prism.

This effect is schematically illustrated in Figure 6. Of course, when turning the prism's refracting angle to the left, warm and cool colours will swap.
Neither green nor magenta manifest themselves in this simple experiment with prismatic edge colours. Goethe considered these two complementary edge experiments as basic, because an edge is the most elementary black and white contrast conceivable. (The reader that is inclined to verify all this by experiment may discover that prismatic colours only appear at locations of contrast.)

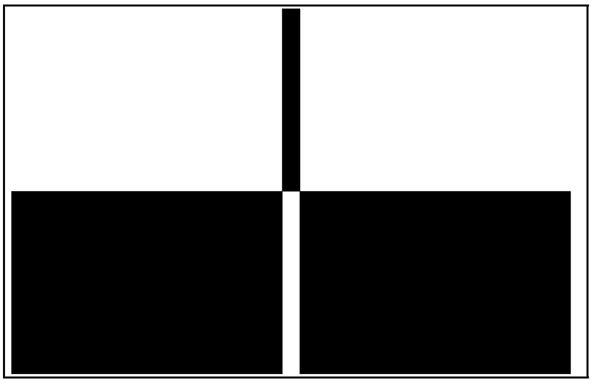


Figure 7 - Observe through a glass prism.

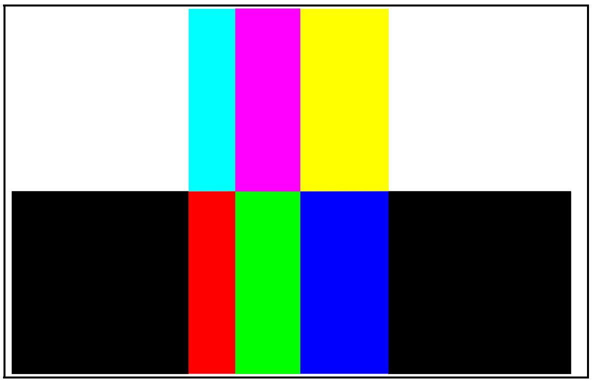


Figure 8 - Figure 7 seen through a prism.

Figure 7 presents two slits: a somewhat uncommon dark slit on a light background (top) and the regular bright slit on a dark background (bottom). Observed through the prism (refracting angle to your right), the top slit is seen split up in the additive primaries cyan, magenta and yellow, an appearance sometimes referred to as the "Goethe spectrum". The bottom slit will present the familiar "Newton spectrum" with red, green and blue violet: the additive primaries. This effect is schematically illustrated in Figure 8.

Making after images of each prismatic phenomenon, while looking through the prism, will again show that complementary colours swap: the Goethe spectrum becomes the Newton spectrum and vice versa showing a top-down, bottom-up reversal of colours. This effect was also demonstrated with the complementary coloured squares in the previous section on the physiological level of complementary colours.

Please note that each slit, observed through the prism at an adequate distance (in order to sufficiently limit the slit's angular width), virtually displays only three colours. In fact we are looking at the spectral distribution of the colour sensitivity (the spectral response) of our own eyes! These prismatic experiments reveal two colour triplets as the basis of our colour vision: red, green and blue violet versus yellow magenta and cyan blue.

Goethe considered these two experiments with the complementary slits as the more complex ones (and thus not representing basic phenomena), because the angular width of the slit is an additional parameter that controls the observed results. This view opposes the modern view that only takes the narrow slit Newtonian spectrum into account as an explanation of colour vision.

6. THE BASIC COLOUR WHEEL

The colour wheel probably is a medieval invention [6], but the first exact colour wheel is much more modern, although almost a few centuries old.
When one circles clockwise through the subtractive and additive colour mixing plates in Figure 1 and Figure 2, the 6 primaries (3 additive and 3 subtractive colours) are traversed in a lawful order: magenta, red, yellow, green, cyan blue, blue violet, and so on. So, together, the three complementary colour pairs encompass the basic colour wheel as shown in Figure 9. Try making an after image of it!

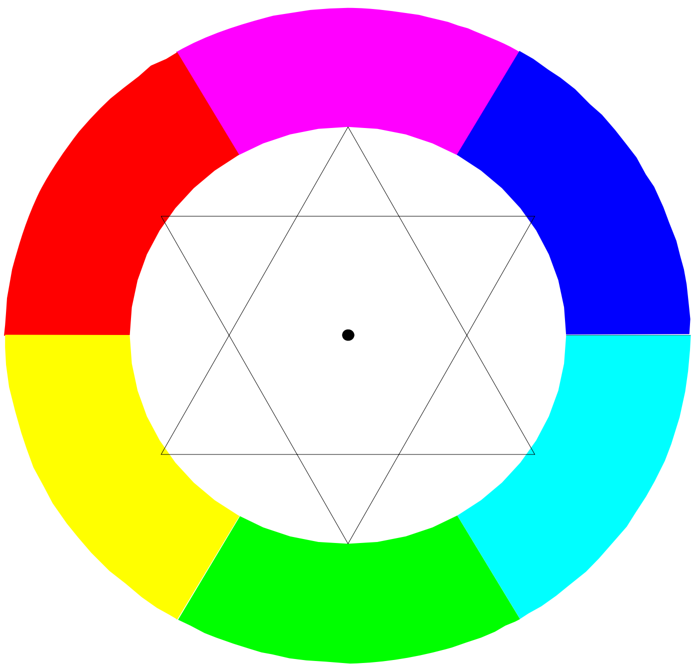


Figure 9 - Goethe's colour wheel with two primary triplets:
The subtractive Ye, Ma, Cy and the additive R, G, B.

In fact Figure 9 constitutes the colour wheel that Goethe published about two centuries ago in his much debated, but not at all obscure Theory of Colours [7- 9]. It is the first colour wheel that is based on exact and unbiased observation of colour phenomena and it is the colour wheel that still enjoys the greatest educational value. Rarely is it realised that the honour of composing this colour wheel is due to Goethe.

The main aspects of Goethe's colour wheel are:

- As they should, the complementary colours are diametrically opposed in the colour wheel: red - cyan blue, green - magenta, blue violet - yellow.
- Each colour in the wheel can be obtained by (either additively or subtractively) mixing its neighbours. (Goethe, of course, did not yet understand the processes of additive and subtractive colour mixing. These laws were only discovered by Helmholtz and Maxwell more than a century ago [10 - 13]).
- Warm, active colours are on one side of the colour wheel, cool, passive colours on the opposite side of it, and they are separated by the two opposite neutral colours: green, which appears neither warm nor cool, and magenta, which appears warm as well as cool.

7. WHY ARE ADDITIVE COLOURS DENOTED BY RED, GREEN AND BLUE?

The additive primaries, as known from our TV and computer screens, are generally denoted as red, green, and blue (RGB). However, actually, the choice for a (deep) blue phosphor is made because no adequate blue violet phosphor is available. The additive primaries are really **red**, **green** and **blue violet**. So, the "B" in RGB stands for blue violet rather than for what we generally understand by Blue. Printing Figure 1 or Figure 2, will show that the printed "B" is much more blue violet than the screen "B". No wonder, the printed "B" results from mixing the colour printer toners magenta and cyan blue!
Imagine how confusing it must be when the subtractive primaries are erroneously denoted by: red, yellow and blue, while the additive primaries are denoted by red, green and blue.

* In fact, the subtractive "blue" is **cyan blue** and the additive blue is **blue violet**.
It may be obvious that the use of the same colour term "blue" for both subtractive and additive primaries is too confusing to be of any use.
* And, in fact, the subtractive "red" is **magenta** and the additive red is really **red**.

It may be also obvious that using the same colour term "red" for both subtractive and additive primaries is just as confusing. Actuality, **red**, **green** and **blue violet** are the colours of the spectral long, middle and short wavebands that the photoreceptors in our retina are sensitive to [14]. In 1802 Thomas Young was the first to recognise this fact [15]. These receptors are the cone cells in our retina, so called because of the cone-like shape of the receptive part of the cells. Blue violet (Newton and many after him just call it violet [16]) is the extreme waveband that we perceive at the short wave side of our visible spectrum; this defines our colour sensation of the primary blue violet. The exact blue violet colour band is displayed when we carry out the prismatic experiment described in section 5.

Our retina cone cells derive their specific sensitivity for the long, middle and short wavebands from the presence of three different light sensitive pigments, that are photo-chemically bleached by absorbing red, green and blue violet light. And indeed, the sensitivity of a pigment for a certain colour can only be achieved if it absorbs this colour, otherwise it would be "blind" (transparent) for it. Now imagine what pigments absorb red, green and blue violet? Not surprisingly, red is absorbed by a cyan blue pigment, green is absorbed by a magenta pigment, and blue violet is absorbed by a yellow pigment. So, deep in our eyes, in their retina, the subtractive primaries are hidden. Our eyes derives their sensitivity for red, green and blue violet light thanks to yellow, magenta and cyan blue pigments: together, the six primaries that make up our basic colour wheel.

8. WHAT IS THE ORIGIN OF THE RED, YELLOW AND BLUE MISCONCEPTION?

From old the colours red, yellow and blue are considered as the primary colours. Already in the beginning of our era and maybe much earlier it was known that, by mixing red (cochineal/kermes), yellow (safflower) and blue (indigo) a large gamut of new colour shades could be derived in dying textiles.

It was only in the beginning of the 18th century that the French painter and graphic artist Le Blond (1667-1741) made the first three-colour prints by the overlapping printing of three gravures with transparent yellow, red and blue inks in register. It was Tobias Mayer (1723-1762) who, for the first time (1758), undertook a systematic arrangement of the primary colours in a colour triangle, and who gave a proper definition of the concept primary colour, discussed in the section 1.

At the time, the empirical search for the primary colours resulted in the selection of crimson (red), gummite (yellow) and Berlin blue. Of all available colours, these three appeared to yield the largest colour gamut: greens from gummite and Berlin blue, oranges from gummite and crimson. Alas, crimson and Berlin blue did not yield violets, but rather smudgy brownish tints, as shown in Figure 10.

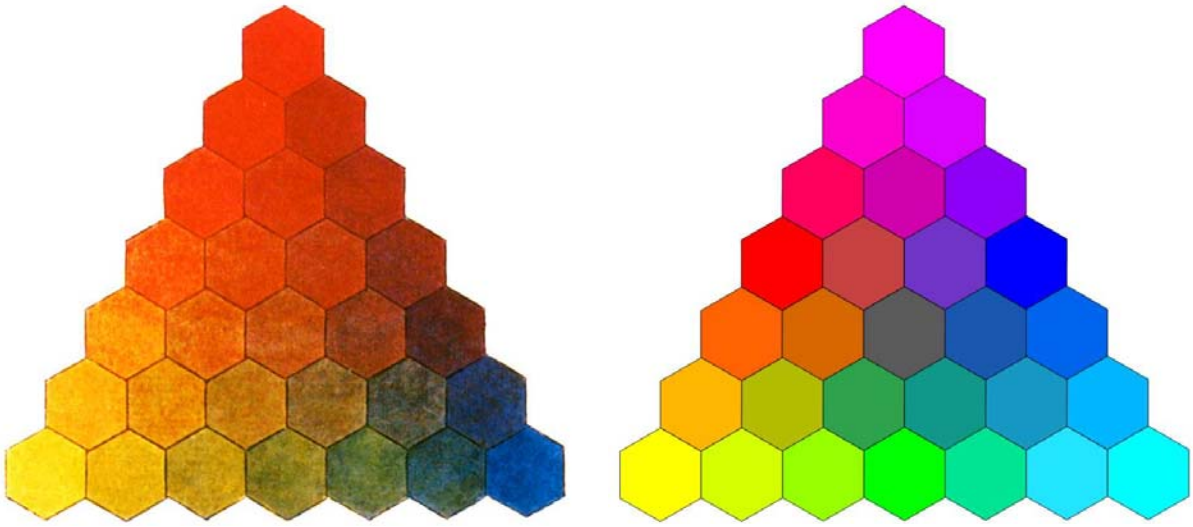


Figure 10 - Tobias Mayer's colour triangle with red, yellow and blue "primaries" published by Georg Christoph Lichtenberg in 1775 (left) and a colour triangle based on the subtractive primaries magenta, yellow and cyan (right).

The colour magenta (Fuchsin) was chemically synthesised only in 1859. Its name is derived from the battle of Magenta (North-Italy, 1859) in the French-Austrian war. The French chemist Francois-Emmanuel Verguin synthesised this colour in that same year and coined it Magenta in memory of the 10.000 war victims. Soon it appeared, that magenta was a primary colour and not red. Magenta is now the internationally adopted name for one of the subtractive primaries.

The historical tradition that denotes red, yellow and blue as subtractive primaries has long appeared erroneous. Yet, this tradition is leading its own delusive life, wholly detached from exact observation and professional disciplines. Unfortunately, in numerous cases one finds red, yellow and blue applied as primaries (which gives awful results) or denoted as primaries (which causes enormous confusion). Famous victims of this erroneous conception are the artists Piet Mondriaan and Johannes Itten.

I trust this contribution will help disentangle the existing confusion. I am interested to receive any comments and I will be glad to answer any questions.

Who is afraid of red, yellow and blue? ***We*** should be, it is an abominable error!

Manuscript created 4 March 1996
Last revision: 8 December 2006

9. References

1. Heinwig Lang, Drei Farbsysteme des 18. Jahrhunderts von Mayer, Lambert und Lichtenberg, Farbe + Design, Ausgabe 15/16 1980, p. 50-59.
2. D.L. MacAdam, Colour Measurement, Theme and Variations, Springer series in Optical Sciences, vol. 27, Springer Verlag, Berlin (1981).
3. M.H. Wilson, R.W. Brocklebank, Goethe's Colour Experiments, discourse given at the 42nd Physical Society Exhibition 1958, delivered on March 24 1958, reprinted in the Year Book of the Physical Society 1958, p. 3-12.
4. Michael H. Wilson and R.W. Brocklebank, The phenomenon of the coloured shadows and its significance for colour perception, Die Farbe 11, nr. 1/6, p. 143-146 (1962).
5. Michael H. Wilson, Colour is where you see it, Tagungsband Luzern 1965, p. 991-1001, Goethean Science Foundation, Clent, Stourbridge (Worcs.), England.
6. Charles Parkhurst and Robert L. Feller, Who invented the Colour Wheel?, Colour Research and Application, Vol. 7, No. 3, Fall 1982, p. 217-230.
7. Johann Wolfgang von Goethe, The Theory of Colours, MA:MIT Press, 1970.
8. Arthur G. Zajonc, Goethe's theory of colour and scientific intuition, American Journal of Physics, Vol. 44, No. 4, p. 327-333, April 1976.
9. Arthur Zajonc, Catching the Light - The entwined history of light and mind, chapter 8, Bantam Books, February 1993.
10. Hermann von Helmholtz, Ueber die Theorie der zusammengesetzten Farben, Poggendorfer Ann., LXXXVII, p.45-66 (1852), onder dezelfde titel gepubliceerd in Archiv fur Anatomie, Physiologie und Wissenschaftliche Medicin p. 461-482, Berlin (1852).
11. Hermann von Helmholtz, Ueber die Zusammensetzung von Spectralfarben, Ann. der Physik und Chemie, band XCIV, nr. 1, p.1-28 (Tafel I), (1855), (Theilweis vorgetragen in der Zusammenkunft der British Association zu Hull im September 1854.)
12. James Clerk Maxwell, Experiments on Colour, as perceived by the Eye, with remarks on Colour-Blindness (with plate VI), Trans. Edinb. Roy. Soc., XXI, part II, p. 275-297 (1855).
13. Hermann von Helmholtz, Handbuch der Physiologischen Optik, #20 - Die Lehre von den Gesichtsempfindungen, p. 281, Leipzig (1867).
14. H.J.A. Dartnall e.a., 'Microspectrophotometry of Human photoreceptors'; Colour Vision, physiology and psychophysics, p. 69-80; ed. J.D. Mollon and L.T. Sharpe, Academic Press, London/New-York (1983).
15. Thomas Young, Lecture XXXVII, On Physical Optics, p. 434-446, Plate XXIX, fig. 427, Lectures Vol. I (1807).
16. Sir Isaac Newton, Opticks or A Treatise of the Reflections, Refractions, Inflections & Colours of Light, based on the fourth edition, London (1730), Dover Publications, Inc., New York (1952).