WHAT IS COLOUR?

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1. The History of Colour

Already more than 20.000 years ago the people in the caves of southern France used colour in their paintings. About 2000 B.C. the Chinese used the five colours yellow, white, black, red and blue to denote the ranks of state officials, with yellowed reserved for the emperor only. Green also had a special role, it was the feminine colour, hence not on the same level as the others but much used in poetry.
In Europe, Leonardo daVinci in his Trattata della Pintura (1519) divided his pigments in six groups: white, yellow. green, red, blue and black. So did Elias Brenner, a miniature painter at the Swedish court, when he in 1680 produced the first known colour chart in the world, illustrating his pigments with small painted samples. Meanwhile the Swedish professor and clergyman Forsius had described a three-dimensional colour space with a verical white/black axis in the centre, perpendicular to a circle with four main hues: yellow, blue, red and green.
In the 17^{th} century, Newton made his famous prism experiment and the English printer Moses Harris made the first three-colour prints in the western world, unknowingly imitating a process developed in China three hundred years earlier.
The 19^{th} century saw the Goethe's philosophical approach to the description of colour and the development of both the theories of both Helmholtz and Hering for colour vision and Grassmann's spectral analysis of the physical spectra generating colours.
The 20^{th} century has marked the breakthrough of our knowledge about the physiology of colour vision and also a widespread use of colour, not only in art and fashion but also in science and technology. Colour has e.g. become the natural mode in newspaper illustrations.

2. What is colour?

Newton´s prism experiment is often described as "splitting the white sunlight into its coloured components". But what Newton really found was that *The rays are not coloured, in them is only a capacity to evoke this or the other colour,* when acting on the human sense of vision. Erwin Land, the engineer behind the Polaroid camera, found that the colour seen by an observer only to a limited extent depends on the spectral composition of the light flux entering the eye, but that colour is generated in the brain. According to W D Wright: *"... colours cannot exist unless there is an observer to perceive them."*
Therefore, *the true meaning of colour is that of a percept,* usually - but not always! - generated by a physical stimulus, whose spectral composition is determined by various pigments and colorants (which are *not* colours themselves). *Colour is what we see*
Colour vision is basically a *psychological* phenomenon, normally caused by *physical* entities in the external world, which are evaluated *physiologically* in the sense of vision. Colorimetry is a *psychophysical* simulation of colour vision. Bearing this in mind, let us study the four aspects of colour : *physics, physiology, psychology* and *psychophysics*.

3. Interdisciplinary colour

3.1 The physical cause of colour

Light and colour are perceptual phenomena stimulated by electromagnetic radiant energy with wavelengths between 400 and 800 nanometers. When we are observing physical objects in our environment, the incident flux from a light source is transmitted or reflected by the object according to its transmittance or reflectance function, and the stimulus function can be calculated as the product of the illuminant and object functions.
In the eighteenth and early nineteenth centuries there was a firm belief among scientists, that given a complete description of the physical properties of the radiant energy, it would also be possible to describe the appearance of the evoked light and colour percepts.

3.2 The psychological description of colour appearance

As colour is a mental phenomenon, it belongs to the sphere of psychology. My text-book on Optics at the Technical University in Stockholm - written by a German physics professor - began by a bedroom experiment. When you go to bed at night and pull the blanket over your head, you will not experience complete darkness; you will see lots of colours, to which there is no physical cause. There is no direct and immediate causality between physical stimuli and perceived colours!

This and other similar phenomena lead the German physiologist Ewald Hering to oppose (in 1874) against the claim of the physicists that light and colour could be described in physical terms. "*For a systematic grouping of colours, the only thing that matters is colour itself. Neither the qualitative nor quantitative physical properties of the radiation are relevant.*" Hering studied the colours and found - among the millions of them - six "unique" colours, *white, black, yellow, red, blue* and *green* (cf China, daVinci, Forsius, Brenner etc.!). No one of them showed any similarity to any of the other five. All other colours were similar to one, two, three or four of the unique colours and could be described by these similarities.

Of the unique colours, white and black are *achromatic* and form the end points of a scale of greys, with increasing blackness and a complementarily decreasing whiteness. The remaining four unique hues are *chromatic* and divide the hue circle in four quadrants, with red opposite green and blue opposite yellow. No colour can show both redness and greenness, or both blueness and yellowness. So Hering's system was described as "opponent".

3.2.1 NCS - a method to describe colour appearance

Hering proposed a "natural system of colour appearance", which he combined with a theory for the physiological process of vision. The physiological part of his theory may have been modified, but the appearance part was further developed in the 1960-ies by a Swedish team (Hård, Sivik, Tonnquist) to the modern NCS (Natural Colour System), also illustrated by a colour atlas.

In NCS, Hering's unique colours are renamed 'elementary colours'. The similarity of any other colour to these is given by the corresponding 'elementary attributes`: the achromatic whiteness, blackness and the chromatic yellowness, redness, blueness and greenness. Each attribute is given a scale from 0 to 100. A colour cannot have more than two chromatic attributes; the sum of them is called the *chromaticness* of the colour, also in the interval 0 ..100. The quotient between the chromatic attributes defines the hue on a scale 0 ... 100 between each pair of adjacent unique hues on the hue circle. In this way, the appearance of a colour can be described logically by a notation, consisting of two figures for blackness, two figures for chromaticness and two figures between two capital letters for the hue:

2060-Y70R

denotes a rather light colour with a low blackness of 20%, a moderate chromaticness of 60% and an orange hue more reddish than yellowish.

1715 colour samples are shown in the NCS atlas, which is now distributed in 30 countries all over the world.[1] But when using a colour atlas, it must be remembered that the visual effects described in the physiology section may influence the appearance of the colour samples. Therefore, designers prefer to use the separate samples that are available in a number of sizes up to A4.

The NCS is the only colour system in full compliance with the physiological facts of colour vision. It is therefore chosen to illustrate the psychological aspect of colour. We will later on describe also other colour systems, even if these are not completely perceptual.

3.3 Psychophysical measurement of colour stimuli

The natural pathway from the physical stimulus to the psychological percept is through the physiology of vision; but until the mid-twentieth century this was not well investigated. Instead, an alternative way was opened, based on Grassmann's studies of the relationships between physical stimuli in a tristimulus (visual) colorimeter, where an observer could mix the amounts of three given stimuli to "match" (look equal to) a given reference stimulus. In this way and averaging the data for 26 observers, the English scientists Guild and Wright obtained a set of three "spectral matching functions" defining the normal human observer.

3.3.1 CIE - the measurement of colour stimuli

The spectral matching functions were used by the CIE (International Commission of Illumination) to define human colour vision by a "standard observer" . The CIE also defined a set of "standard illuminants". No real observer strictly follows the standard observer, and no real illumination exactly follows the standard requirements, but they are the only possibility to compare measurements made on different instruments in different laboratories and are the basis of instrumental colorimetry. The recommendations were made in 1931 and are now a formal or *de facto* standard all over the world..

The CIE method can be applied both directly on the light flux from a light source and on the transmittance functions of filters or reflectance functions of coloured surfaces. Any of these multiplied by the illuminant function gives the stimulus function, which in turn is multiplied wavelength by wavelength by the three spectral matching functions. The accumulated products give three tristimulus values called X;Y;Z., usually further transformed to some other set of co-ordinates more suitable for the actual task. As colour space is three-dimensional, there must always by a triplet of such co-ordinates, called a "colour valency". Frequently used to-day are the CIELUV- and the CIELAB stimulus spaces; CIELUV in the first place for displays and other projected colour stimuli, CIELAB for reflected stimuli from coloured objects..

CIE 'valencies' are excellent in predicting when two stimuli may give equal colour percepts (look the same), but they are not able to describe the visual quality of these percepts (colour appearance). For that we need a descriptive colour system such as the NCS mentioned above.

3.4 The physiology of colour vision

In the eye, the receptors of the incident radiant stimuli are the rods and cones of the retina. Whereas the rods all have the same sensitivity over the visual spectrum, the cones are of three kinds with different spectral response functions.

[1] The NCS distributor in Italy is
Roberto Salardi
Instituto del Colore (NCS Italia)
Via Benigno Crespa 30/2 Tel. 02-6900 8877
I-20 159 MILANO Fax 02-6900 1022

Already around 1800 it was believed (Young and Helmholtz) that this was the basis of colour vision and that the sensitivity functions were evenly distributed over the visual spectrum. But one didn't know how to combine this with either Grassmann's tristimulus theory nor Hering's concept of four unique hues.
Finally, in the mid-twentieth century Smith and Pokorny were able to measure the sensitivities of individual cones and found three functions, often called α, β, γ, overlapping for short wavelengths but encompassing various bandwidths of the visual spectrum. The major part of colour vision could be attributed to the difference in signals received by the β and γ cells, although their sensitivity functions are rather similar, both with maximum in that part of the spectrum which Newton called "green-makers".
The signals are thought to interact with each other already in the retina to form three bipolar signals: blue/yellow, red/green and black/white, which are transmitted to the visual cortex in the back part of the brain. This means a strong support to Hering's opponent colour theory.
But there is no direct and absolute relation between stimulus and percept. In the lecture, several illustrations were shown to demonstrate, how

- simultaneously seen colours in a pattern influence each other, sometimes increasing their contrast, sometimes reducing contrast (assimilation),
- the sharpness/diffuseness of the contoujr of a colour field may change its perceived colour,
- the removal of an object from the visual field may cause the perception of a successive contrast (the green elephant has a pink elephant as its after-image).

3.4.1 Why colour vision?

According to the evolution theory, colour vision was developed as a condition for survival. Our ancestors learned to see and name the colours they needed to recognise inorder to find their food and to avoid the perils in the environment. Now we more and more use the colours to enhance the quality of life and as a fringe of luxury.

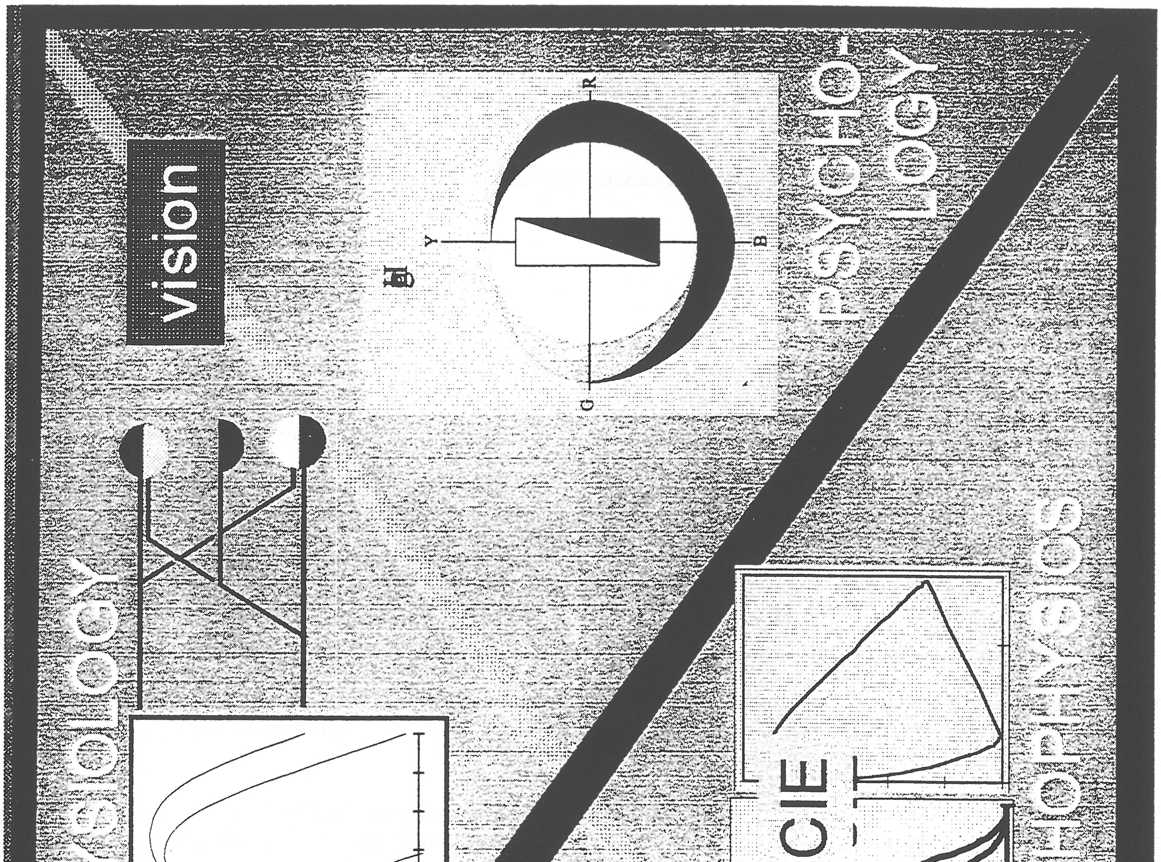
4. Other colour systems

In addition to the perceptive NCS and the psychophysical CIE system there are a number of other systems. Several of them pretend to be perceptive, but are so only in a restricted sense: the spacing of colour samples in the illustrating atlas are selected in perceptive experiments, but the selected colours are to be defined in CIE terms only, as there are - with the exception of white and black - no basic perceptual references like Hering's unique colours in the system.
(The NCS is the only system capable to describe colours seen under arbitrary conditions; the validity of all other systems is restricted to the particular conditions of illumination and viewing for which the colour samples were selected. However, the samples in the NCS atlas are subject to the same restrictions as all other colour samples.)

This is the case with the wide-spread American *Munsell* system, based on the perceptual variables Value (lightness), Hue and Chroma (chromatic strength - as an absolute measure compared with the relative measure of NCS chromaticness). The hue scale has five fundamental hues (red, yellow, green, blue, purple), which are claimed to be equally spaced, but were not selected by perceptive criteria but in a physical experiment. The Value variable may be important in some design work, but most designers prefer the blackness concept of the NCS, especially to select harmonious colours of different hues.
The German DIN system has the variables Buntton (=hue, but colorimetrically defined), Dunkelstufe (similar to NCS blackness) and Sättigung. The hue circle is the only one correctly established on the criterium of equal spacing. The results deviates considerably from the spacings of both NCS and Munsell. On the other hand, it has not been proved that a strictly equal spacing of hues has any significance in design work; on the contrary, the Hering unique hues have been found important as natural dividers in colour space. The Sättigung is also colorimetrically defined and constitutes so called shadow series in stimulus space. At the same time, this leads to a congestion of nearly equal dark colour samples around black.
Lately, several illustrations of CIE co-ordinates by colour samples have become popular, e.g. the German RAL Design System, representing the CIELAB space. A serious drawback with all such systems is that if hue is defined colorimetrically by a given angle in stimulus space, this does *not* mean that the colours look as being of the same hue. Also, the chromatic a,b-axes of the space deviate strongly from the natural percptive directions of elementary hues.

5. Colour names and colour coding

It is estimated that human colour vision under favourable conditions of comparison can distinguish around 10 million colours. The standard NCS notation, using integer values only, can describe more than 2 million colours and the NCS atlas contains 1715 colour samples.
In contrast, the number of colours that can be securely identified, given only a single colour name, is very low. In an extensive linguistic study of colour names in many languages from different cultures, Berlin and Kay found, that the first colour names to appear are words for white and black, always followed by some word for red. Then comes yellow, green and blue, i.e. the same fundamental colours as designated by daVinci, Brenner, Hering etc. These are also the only colours that can be used in a colour coding system with high security.
Then follow five other colours found by Berlin and Kay as belonging to the basic colour categories: orange, brown, pink, purple and grey. These may also be used as coding colours with fairly high security. If more colours are needed in a coding system, they must be accompanied by some additional clues in form of e.g. the geometrical shape of the colour signal


vision
PHYSIOLOGY
PSYCHO-
LOGY
CIE
illumination
reflexion
stimulus function
optics