H31: Putting Numbers to Colour: CIE RGB

Numerical methods of describing colour are used to communicate colour information without the need for physical samples. Ideally the numbers should by easily interpreted in terms of attributes such as lightness, chroma or hue.

Three things contribute to the colour appearance of an object, as illustrated in Figure 1.

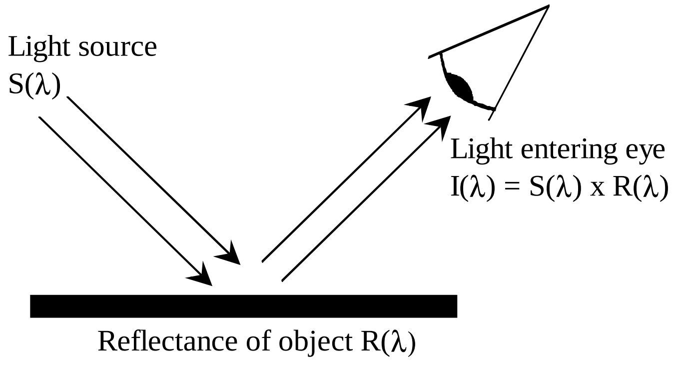

Figure 1: How coloured light reaches the eye

Nature of the illumination:
The nature of the illumination can be characterised by the *spectral power distribution S(λ)* of the light source.

Optical properties of the material:
At each wavelength (λ), the object reflects a certain fraction of the incident light toward the eye and this can be characterised by *the reflectance spectrum*.

R(λ) Response of the eye:
The response of the eye is characterised by a set of three *colour matching functions.*

It should be remembered that the perception of the colour of a surface depends on number of things other than the spectrum of the light entering the eye. Some of the other influences are the colour of the neighbouring areas (lateral inhibition), the size of the image (rod and cone distribution) and the intensity of the incident illumination. The CIE system of numerical specification described here does not take these secondary influences into account and so the numbers obtained describe the colour of an object or image under specific, reference viewing conditions.

The RGB system and the XYZ system developed during the 1930's and adopted by the *CIE (Commission Internationale de l'Éclairage)* were based on the principles of *additive mixing of coloured lights* and the trichromatic theory of colour vision. In many ways, the CIE system provides a description of how to reproduce the colour sensation rather than a description of colour appearance.

The most familiar example of colour reproduction by additive colour mixing is colour television. The combination red light, green light and blue light emitted by the display screen produces all the colours seen on the screen.

Maxwell's suggestion

As early as the 1860's, Maxwell suggested that that the amounts of standard red light, green light and blue light in an *additive mixture* that matches the colour appearance of an object would provide a specification of the colour of the object.

The effects of the additive mixing of coloured lights can be described by algebraic equations based on three empirical laws known as *Grassman's Laws (1853)*.

> Light from colour stimuli that have the same colour appearance will have the same effect in additive colour mixing, irrespective of their spectral composition.
>
> The additive colour mixing properties of a colour stimulus can be fully described by three independent variables (tristimulus values).
>
> If the contribution of a component in an additive mixture of colour stimuli is changed gradually , then the tristimulus values of the mixture change in linear proportion.

Primary light sources
To realise Maxwell's concept of specifying a colour by the amounts of red, green and blue lights in an additive mixture that produces a matching colour stimulus, it is necessary to define the nature of the light sources.

A set of three *Primary Light Sources* is defined as a set where the colour of any one of the set cannot be reproduced by a mixture of the other two.

For example:- red, green and blue light sources do form a primary set

whereas:- red, green and yellow do not form a primary set

The yellow is not a primary since the same colour effect can be produced by combining light from the red and green sources.

CIE RGB system

Ideal primaries
Ideal primaries are defined as the set that is capable of producing the widest gamut of colours when mixed in different proportions. The set of additive primaries selected by the CIE for practical measurements consisted of:-

monochromatic red light of wavelength,	700.0 nm
monochromatic green light of wavelength,	546.1 nm
monochromatic blue light of wavelength,	435.8 nm.

The first wavelength can be produced by passing light from an incandescent lamp through a filter. The last two wavelengths were chosen because they occur in the spectrum of a mercury arc lamp and can again be selected with appropriate filters.

Tristimulus units (T units)
To simplify colour mixing calculations, special red, green and blue colour-matching units were defined called tristimulus or T units. The units are defined so that a mixture containing equal T unit amounts matches the appearance of an equal energy white light source. An equal energy white source emits the same intensity (Watts) at each wavelength in the visible spectrum. The units are :-

1 T_R (red),	represents 1.0000 cd/m^2 of the red source
1 T_G (green),	represents 4.5097 cd/m^2 of the green source
1 T_B (blue),	represents 0.0601 cd/m^2 of the blue source

Colour matching functions
The colour matching functions represent the amounts of the primary light sources, in T units, needed to match the colour sensation produced by light with a narrow band of wavelengths centred on λ.

A possible experimental arrangement for determining the wavelength dependence of the function is illustrated in Figure 2.

The calibration task was undertaken separately by J. Guild at the National Physical Laboratory and W. D. Wright at Imperial College in a famous series of experiments.

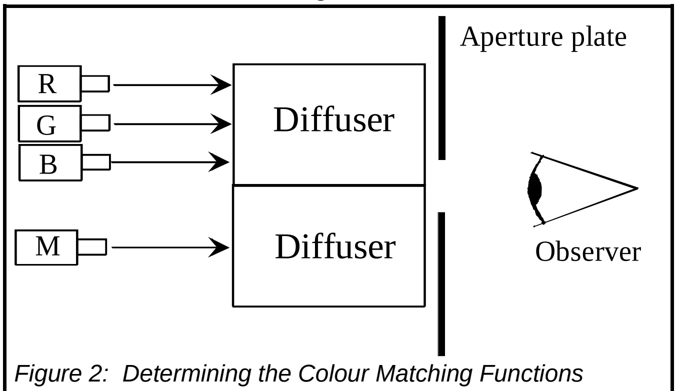

Figure 2: Determining the Colour Matching Functions

Each of them used several observers (Guild 7 and Wright 10) who adjusted the composition of the mixture of light from the three primaries until the mixed light matched the appearance of the monochromatic light.

The colour matching functions, $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$, adopted by the CIE are plotted against wavelength in Figure 3. Notice that the values are negative at some of the wavelengths, this occurs when a simple additive mixture of light from the three primaries could not match colour produced by the monochromatic light.

When a match is not possible it is necessary to reduce the colour saturation of the monochromatic light by adding light from one of the primaries to the monochromatic light.

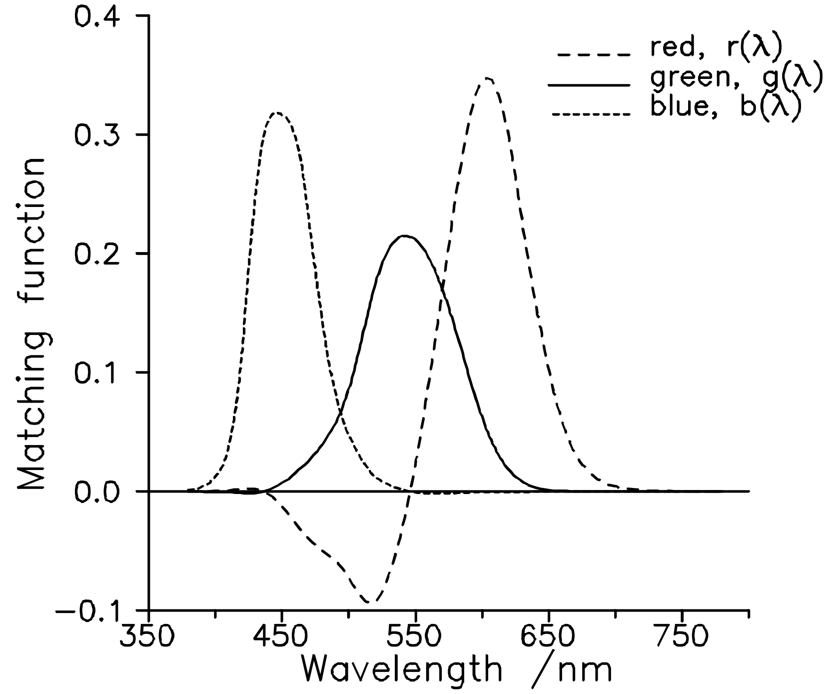

Figure 3: The CIE 2°colour matching functions

The appearance of the de-saturated monochromatic light could then be matched by a combination of the other two primaries. When this occurs the amount of the primary added to the monochromatic light appears as a negative number in the colour specification.

Drawbacks of the CIE RGB system

The RGB system has a number of practical limitations.

1. A large section of the gamut of visible colours has one or more values of R, G or B negative.
2. The luminosity (brightness) response function of the visual system is not represented by either $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ or $\bar{b}(\lambda)$
3. The values of R, G and B are not easily associated with visual attributes such as lightness, colour intensity (chroma) or hue.
4. The difference between the R, G and B values for two coloured surfaces is not proportional to the visual difference in appearance between the two surfaces.

In 1931 the CIE devised an adaptation, CIE XYZ that addressed the first two drawbacks.

It was 1976 before two other systems, CIELAB and CIELUV, were agreed that addressed the last two drawbacks.

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