CHAPTER 7

The Colour Triangle

7.1 Introduction

In Chapters 2 and 4 the errors of trichromatic colour reproduction by both the additive and the subtractive principles were considered in terms of the assumed sensitivity curves of the three types, ρ, γ, and β, of retinal cone. This approach to the subject has the advantage of being direct and simple, but it requires some assumptions concerning the eye, and is of a qualitative, rather than a quantitative nature. For a quantitative approach it is necessary first to consider in some detail the phenomenon of trichromatic colour matching. Before we do this, however, a brief consideration of some aspects of colour terminology is advisable (CIE International Lighting Vocabulary, 1970).

7.2 Colour terminology

It is generally agreed that colours have three main perceptual attributes. The most obvious is *hue*, denoting whether the colour appears red, orange, yellow, green, blue, or purple (or some mixture of neighbouring pairs in this list). *Colourfulness* denotes the extent to which the hue is apparent; colourfulness is thus zero for whites, greys, and blacks, is low for pastel colours, and is (normally) high for the colours of the spectrum. *Brightness* denotes the extent to which an area appears to exhibit light; brightness is thus, usually: extremely high for the sun, very high for many other sources of light, high for whites and yellows, medium for greys and browns, and low for blacks. (In the past *luminosity* was sometimes used for this attribute instead of brightness.)

Objects viewed in a high level of illumination generally look brighter than when viewed in a low level, even when the observer is fully adapted to each level; but, in the very important task of recognizing objects, their brightnesses relative to one another are given great attention. Thus, a piece of grey paper seen in sunlight is much brighter than when seen by indoor daylight on a dull day; but it still looks grey, not black, on the dull day because its brightness is judged relative to other objects in the scene. This concept of relative brightness is so important that the term *lightness* is reserved for it, and is defined as the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white (or highly transmitting, in the case of transparent objects).

When changes are made in the illumination level to which an observer is adapted, changes occur, not only in the brightnesses of objects, but also in their colourfulnesses. Thus, a scene that looks very colourful in bright sunlight, looks less so in dull cloudy daylight, much less so at twilight, and at moonlight levels looks almost devoid of colourfulness altogether. But, in the important task of recognizing objects, their relative colourfulnesses are given great attention. Thus, a red tomato, seen in sunlight, is much more colourful than when seen indoors on a dull day; but we still perceive it as red, not pink, on the dull day, because its colourfulness is judged relative to other objects in the scene. This attribute of relative colourfulness is called *chroma*; it is defined as the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white (or highly transmitting). Thus, although the tomato on the dull day has a low colourfulness, it is also evident that neighbouring whites also have a low brightness; and this enables the observer to attribute the low colourfulness to the low level of illumination, and not to some change in the object, which is therefore seen as having constant chroma.

It is also possible to judge colourfulness in proportion to the brightness of the object itself (rather than to that of a white), and, when this is done, the relative colourfulness is termed *saturation*. If the level of illumination on an object varies over its surface, because of the three-dimensional shape of the object or because of shadows, it may be difficult to judge what the brightness of a similarly illuminated white would be except for a few areas. This means that the perception of lightness and chroma is difficult in many areas, but it is still possible to judge the colour of the object in all its areas in terms of its hue and saturation. Thus, in the case of the tomato, its hue, lightness, and chroma may be judged for the part that is normal to the incident light; but its hue and saturation may be judged for every part of its surface. Hence, when judging the uniformity of the colour of the tomato, hue and saturation are likely to provide a more useful basis than hue, lightness, and chroma.

In the case of light sources it is not possible to make any judgements relative to 'similarly illuminated areas', and therefore lightness and chroma have no relevance; the attributes of light sources are therefore restricted to *hue*, *colourfulness*, *brightness*, and *saturation*.

Before the distinction between colourfulness, chroma, and saturation was recognized as requiring different terms, all three attributes were often referred to as saturation (Hunt, 1977 and 1978). The fourth edition of the International Lighting Vocabulary (CIE, in preparation) recognizes the distinctions between the three attributes, and also allows the use of *chromaticness* as an alternative to colourfulness. The adjectives *bright* and *dim* are used in connection with brightness; *light* and *dark* with lightness; and *strong* and *weak* with chroma.

In colour, both the response of the observer (the subject) and the physical nature of the stimulus (the object) are important, and it is necessary to distinguish clearly between these *subjective* and *objective* aspects of colour. The terms hue, colourfulness, brightness, lightness, chroma, and saturation, as described above, are clearly all subjective terms. Objective terms denote quantities obtained with measuring instruments and, unlike subjective attributes, these quantities are unaffected by changes in the adaptation of the observer. It is desirable to measure quantities that correlate with the subjective attributes defined above, and the relevant objective terms are as follows.

Subjective Terms	*Objective Terms*	*Objective Symbol*
Hue	Dominant wavelength	λ_d
	CIE hue-angle	h_{uv} or h_{ab}
Brightness	Luminance	L
Colourfulness (chromaticness)	—	—
Lightness	Luminance factor	β
	CIE lightness	L^*
Chroma	CIE chroma	C^*_{uv} or C^*_{ab}
Saturation	Purity	p
	CIE saturation	s_{uv}
Hue and saturation	Chromaticity	x,y or u',v'

For some of the subjective attributes, two objective terms have been listed; in all these cases the second term (which has the prefix CIE) denotes a measure that is correlated with the subjective attribute more uniformly than is the case for the first term; these more uniform correlates will be considered in detail in Chapter 8. There is no objective term listed to correlate with colourfulness, because no such measure has yet been devised.

Dominant wavelength is defined as the wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with a specified achromatic stimulus (a white or grey), matches the colour stimulus considered. In the case of purple stimuli, the complementary wavelength, λ_c, has to be used, and this is the wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the colour stimulus considered, matches the specified achromatic stimulus. *Luminance* is the luminous intensity in a given direction per unit projected area (the units used are given in Appendix 3). *Luminance factor* is the ratio of the luminance of a colour to that of a perfectly reflecting or transmitting diffuser identically illuminated (by perfect is meant that the diffuser is uniform, isotropic, and does not absorb any light). The more specific terms *reflectance factor* and *transmittance factor* are used for reflecting and transmitting samples, respectively, but in these cases the ratio is that of the light reflected or transmitted by the sample within a defined cone to that by the perfect diffuser within the same cone; if the cone is a hemisphere, the ratio is denoted as the *reflectance* or the *transmittance*; if the cone is very small, these measures are the same as the luminance factor. *Absorptance* is equal to unity minus the transmittance or reflectance. *Opacity* is equal to the reciprocal of the transmittance or reflectance. *Purity* is a measure of the proportions of the amounts of the monochromatic stimulus (or, for purples, of a red and violet spectral mixture) and of the specified achromatic stimulus that, when additively mixed, match the colour stimulus considered. *Chromaticity* is denoted by the proportions of the amounts of three colour-matching stimuli needed to match a colour.

There are occasions when it is extremely important to distinguish between the objective and subjective attributes of colours; but in many contexts only general matters are in view and strict observance of the above terminology would be pedantic. In these cases the subjective terms are used in this book, because they are more widely understood.

In the the Munsell system of colour specification, the variables, although *objective* (they are not affected by the observer's adaptation), have been scaled to be as uniform as possible *subjectively*. Thus, *Munsell Hue* represents perceptually equal hue differences by nearly equal increments; *Munsell Value* does the same for lightness differences, and *Munsell Chroma* for chroma differences. The sizes of the units are such that 1 unit of Munsell Value is roughly equivalent to 2 units of Munsell Chroma, and to 3 units of Munsell Hue for samples of Munsell Chroma 5 (Newhall, 1940). Colour terminology is considered further in Chapter 8.

7.3 Trichromatic matching

If, as in Fig. 7.1 arrangements are made whereby colours can be compared in appearance with an additive mixture of red, green, and blue light, it is found that by varying the relative and absolute amounts of the red, green, and blue lights it is always possible to make the appearance of the mixture identical to that of any chosen colour. A few colours of very high purity appear to be exceptions to this rule, but, as we shall shortly see, they can also be matched by using a special technique.

This phenomenon of trichromatic matching is easily explained in terms of a trichromatic theory of colour vision. For, if all colours are analysed by the retina into only three different types of response, ρ, γ, and β (proportional, presumably to absorptions in three different photo-sensitive pigments), the eye will be able to detect no difference between two stimuli that give rise to the same ρ-, the same γ-, and the same β-signal, no matter how different the two stimuli may be in spectral composition. In fact the spectral difference between two matching stimuli can be quite startling as shown in Fig. 7.2, where a stimulus consisting of power