# 1
Colour perception

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1.1   Introduction

Colour exists only in the mind; it is a perceptual response to light that enters the eye either directly from self-luminous light sources or, indirectly, from light reflected by illuminated objects. The nature of light and the spectral reflectance properties of objects are therefore described in the first part of this chapter. The second part of the chapter is concerned with the physiology and functional properties of the retina in the human eye. Light that enters the eye is sampled by three classes of light-sensitive cells in the retina known as cones. In order to understand colour, it is necessary to appreciate that the effective spectral sensitivities of these cones are not static; rather, they change with the illumination conditions and the responses of spatially neighbouring cells, to name but two factors. Furthermore, the three classes of signals from the cones are processed by the neural pathways that lead from the retina to various areas of the cortex in the brain. Although our understanding of colour processing in the human visual system is sufficient to allow us to predict when two spectrally dissimilar objects will be a visual match, it does not allow us to make reliable predictions of colour appearance. In this chapter, three current problems for the science of colour vision are described: colour contrast, colour constancy and colour appearance.

1.2   The nature of colour

Light is a form of energy. Specifically, it is that part of the spectrum of electromagnetic radiation that our eyes are sensitive to. Radio waves and X-rays, as well as ultraviolet and infrared radiation, are all part of the spectrum of electromagnetic radiation but the human visual system is only capable of sensing a very narrow band of wavelengths in the approximate range 360–780 nm (a nanometer is 10^{-9} metres). The light from any source can be usefully described in terms of the relative power emitted at each wavelength in the visible spectrum. Figure 1.1 shows the wavelengths of the
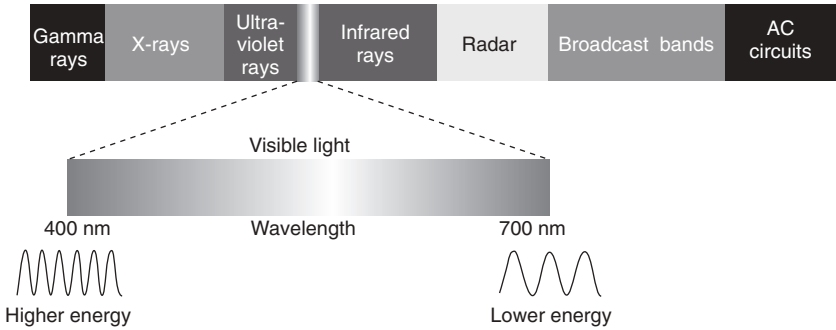
1.1 The electromagnetic spectrum. Only radiation in the range 360–780 nm is visible to the human eye.

visible spectrum and the colours with which we normally associate the wavelengths. However, Newton was famously aware that 'the rays are not coloured'. By this phrase Newton meant that light is not intrinsically coloured; short-wave light, for example, has no intrinsic property by which it is blue but, rather, it may induce in us the sensation of blueness. Under some circumstances, however, short-wave light may appear black or some colour other than blue. It is therefore clear that colour cannot be understood without a study of the properties of the human visual system, since colour exists only in the brain.

The spectral power distribution of daylight varies with geographical position, atmospheric conditions, and with the time of day and year but the set of daylight power distributions is very similar to that emitted by a blackbody[1] heated at different temperatures (Judd *et al.*, 1964). For many light sources it is useful to refer to the temperature (usually expressed in Kelvin) of the blackbody whose radiation most closely resembles that of the light source. This temperature is called the correlated colour temperature (Sinclair, 1997). The radiation of north sky daylight on a cloudy day has a correlated colour temperature of about 6500 K, whereas the light from a tungsten filament bulb has relatively more power at the long wavelengths, which gives it a much lower correlated colour temperature.

1.3   The physical basis of colour

When light strikes an object, some light is always reflected from the surface, at the boundary between the object and air, because of the change in refractive index as the light passes from air to a more dense medium. This surface reflectance has the same relative spectral power distribution as the illumi-

1 A blackbody is a hollow heated chamber with a small hole; as the blackbody is heated, the spectral power distribution of the light emitted from the hole varies.

nating source and may be diffuse or specular in nature. Diffuse reflectance, where the light is dispersed in many different directions, occurs when the surface is rough, whereas smooth glass-like surfaces give rise to specular surface reflectance where the angle of reflection is equal to (but with opposite sign) the angle of incidence of the illumination. The light that is not reflected at the surface enters the body of the object, where further interactions take place. If the material is transparent, some light will pass through the material and emerge at the other side. The most common processes that reduce transparency are absorption and scattering. Absorption is a process whereby light is removed by an interaction with the molecules of the object at an electronic level. Most objects are coloured because this absorption process is more efficient at certain wavelengths than at others, in a way that depends upon the properties of the molecules (Zollinger, 1999). Scattering is a kind of reflection that occurs when particles (or air bubbles) are present in the material. The amount and directional nature of the scattering depends upon the size of the particles and their refractive indices (relative to the medium in which they are contained). Many opaque (non-transparent) white materials are manufactured by adding particles of a white pigment such as titanium dioxide, which has a particularly high refractive index. Translucency is a visual phenomenon that can give materials a milky or cloudy appearance and occurs when the material is partially transparent but exhibits scattering. Further details about the physics of light and its interaction with materials is provided by Nassau (1983) and Tilley (2000) or, for an explanation at the level of quantum electrodynamics, Feynman (1990).

The proportion of light reflected by a sample can be measured using a reflectance spectrophotometer and represents the (physical) colour fingerprint of the sample. A spectrophotometer typically measures the proportion (sometimes expressed as a percentage) of light reflected by the object at each of several equally spaced wavelength intervals. Commercially available instruments typically measure at 31 wavelength intervals centred at 400 nm, 410 nm, 420 nm, . . . , 690 nm, and 700 nm.[2] Most reflectance spectra are smooth functions of wavelength so that it is reasonable to measure the reflectance at wavelength intervals of 5 nm or even 10 nm with little loss of information (Maloney, 1986). For non-fluorescent materials, the spectral reflectance factors are independent of the intensity or spectral distribution of the light source that is used by the spectrophotometer. That is to say, if

2 Many instruments extend the measurements to wavelengths shorter than 400 nm and/or longer than 700 nm. Although the spectral sensitivity of the visual system is usually given as 360–780 nm, at the very short and long wavelengths in this range we are not very sensitive and therefore whether an instrument extends to, say, 760 nm or 780 nm is not usually of great practical importance.

a given object reflects 50% of the light at a given wavelength, this is independent of whether the incident illumination contains 100 or 1000 units of power at that wavelength. The spectral reflectance factor is obtained by comparing the intensity of the reflected light for an object at a given wavelength with the intensity of the light reflected by a perfect Lambertian diffuser.[3]

1.4   The human colour vision system

The light that is reflected by objects or emitted by light sources enters the eye, where it may be absorbed by visual pigments in the photoreceptors, or cones, contained within the retina. The spectral sensitivities of the pigments in the three cone classes play a significant role in the nature of our colour perception. However, colour perception can only be fully understood if the processes that take place in the nervous system that transmits the retinal signal to the occipital lobe of the brain's cortex are studied. A brief review of physiological processes that are important for colour vision is given in this section.
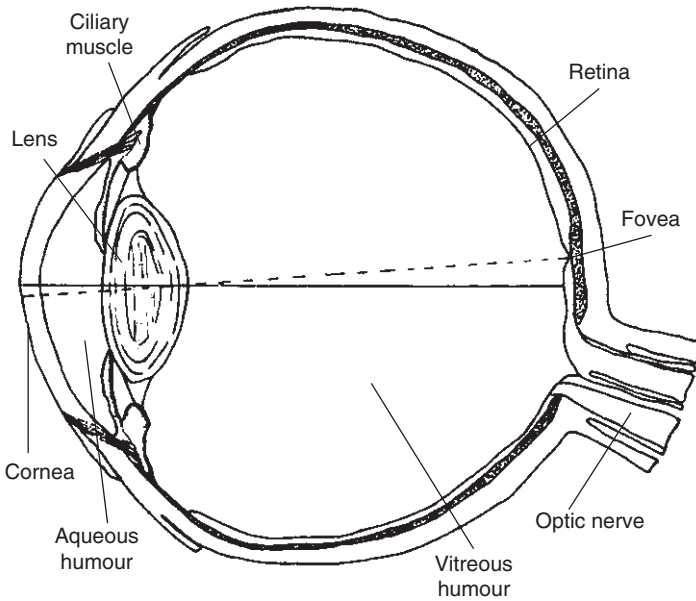
1.4.1 The human eye

The eye is an approximately spherically shaped organ that contains an aperture and a light-sensitive inner lining called the retina. The aperture is at the front of the eyeball and allows light to enter where it can be focused by the lens onto the retina. The front of the eye is covered by a clear layer of tissue known as the cornea through which light must pass before it can enter the eyeball. The main function of the cornea is to protect the eye from injury; however, it also acts to refract the light so that it is focused appropriately at the retina[4]. About two-thirds of the focusing of light by the eye is carried out by the cornea (Meek, 2002). the lens – a crystalline structure that is suspended by the ciliary muscles (see Fig. 1.2) – being responsible for the remainder.

The shape of the lens can be changed as it is squeezed by the ciliary muscles as a way of focusing a sharp image of the scene on the retinal layer that coats the inner surface of the eye. The iris can change size, so that the area changes from about $50\,mm^2$ in dark conditions to about $10\,mm^2$ in

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3 Practically, since perfect Lambertian diffusers are difficult to manufacture and maintain, a white tile with known (the reflectance of the white tile, which is referred to as a secondary standard, is known relative to the perfect diffuser) spectral reflectance is used.

4 The cornea focuses light by being highly curved (more curved than the rest of the eye), possessing a smooth optical surface, and by being highly transparent.

1.2 Schematic diagram of the human eye.

bright sunlight. Although the pupil area can change by as much as a factor of 10 in response to the light intensity, in fact the range of illuminances in which the visual system operates covers many orders of magnitude (e.g. 10 lux in a darkened room to 100000 lux in brilliant outdoor sunlight). Therefore, the change in pupil size can only play a minor role in the adaptation of the visual system to changes in light intensity.

Light is focused onto the retina which includes specialised cells, known as rods and cones, that contain photopigments that undergo a chemical transformation when light of an appropriate wavelength is absorbed. In the rods, the photopigment is based upon the compound known as rhodopsin, and the events that occur when rhodopsin absorbs light have been studied by psychophysical, biochemical, physiological and, most recently, molecular techniques (Bowmaker, 2002). Rhodopsin consists of a protein called opsin and another molecule called 11-*cis* vitamin A aldehyde (also known as retinal). When rhodopsin absorbs light, the rhodopsin, molecule decomposes into opsin and vitamin A. Once a photon has been absorbed by rhodopsin, there is a change from the 11-*cis* isomer to the all-*trans* isomer as the terminal chain connected to opsin rotates. The protein then undergoes a series of transformations to eventually produce all-*trans* retinal and opsin. The bleached photopigment loses its colour and no longer responds to light. Regeneration of the coloured photopigment is very slow and takes

several minutes. Further details about the visual pigments are available in the literature (e.g. Bowmaker, 2002).

The photopigments that are found in the rods and cones have sensitivity functions (see Fig. 1.3) that are approximately bell-shaped functions of wavelength (Stockman, MacLeod and Johnson, 1993). Under normal levels of illuminance (referred to as photopic vision) the responses of the rods become saturated and therefore normal colour vision is mediated by the responses of the cones. However, the rods perform an extremely useful function because at low levels of illuminance (referred to as scotopic vision) the cones do not respond at all and thus night vision is mediated by the rods. The three classes of cone are referred to as being short-, medium- and long-wavelength sensitive in relation to the wavelength of the peak sensitivity of the photopigments. The abbreviated terms *L*-, *M*-, and *S*-cone classes are often used. The spectral sensitivities of the extracted pigments have been measured and found to peak at 420 nm, 530 nm and 560 nm but the effective sensitivities of the cone classes are sometimes given as 440 nm, 545 nm and 565 nm because of absorption by the macula pigment in the retina and by the lens itself.

Rushton (1965) emphasised that, when a photopigment molecule absorbs light, the effect is the same, no matter what the wavelength of the absorbed light might be (Wandell, 1995). Thus, even though a quantum of light at 400 nm possesses more energy than a quantum at 700 nm, the sequence of chemical reactions in response to absorption of a 400-nm quantum is identical to the response sequence to a 700-nm quantum. This important property
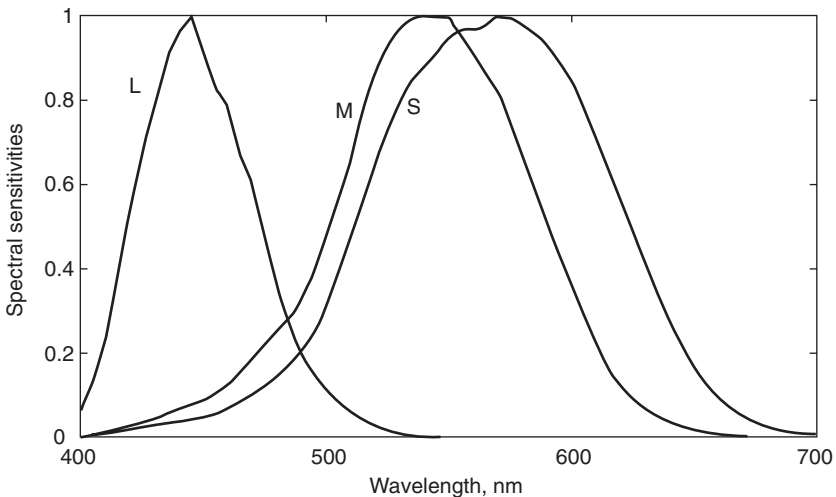
1.3 Spectral sensitivities of L (red), M (green) and S (blue) human cone classes (Stockman, MacLeod and Johnson, 1993).

is known as the *principle of univariance*; a photopigment makes a single-variable response to the incoming light. The photopigment maps all spectral lights (whether single wavelength or broadband) into a single-variable output, the rate of absorption, and thus confounds the independent variables of intensity and wavelength. Consequently, under scotopic viewing conditions, when vision is mediated by a single photopigment in the rods, we cannot discriminate between lights of different spectral compositions that are equally bright. Scotopic vision is monochromatic; we simply see shades of grey. Note, however, that even under scotopic conditions the rod photopigment does not respond equally well to all wavelengths, the sensitivity being greatest for the middle wavelengths in the visible spectrum.

The response of each cone class can be estimated by the integration over the visible spectrum of the spectral sensitivity of the cone's photopigment and the spectral distribution of the energy in the colour signal that enters the eye. If we represent the reflectance $P(\lambda)$, the light source $E(\lambda)$ and the cone spectral sensitivities $\Phi_L(\lambda)$, $\Phi_M(\lambda)$ and $\Phi_S(\lambda)$ each by discrete functions at a number of wavelengths, then the cone responses can be computed by the following simple equations:

$$L = \sum E(\lambda) P(\lambda) \Phi_L(\lambda),$$
$$M = \sum E(\lambda) P(\lambda) \Phi_M(\lambda),$$
$$S = \sum E(\lambda) P(\lambda) \Phi_S(\lambda),$$

1.4.2 Colour vision

It can be misleading to think about the spectral sensitivities of the cones as being static functions of wavelength. It is well known that processes of light adaptation take place in the retina (Wandell, 1995) and the visual system not only adapts to different light levels, it also adapts to colour (Hurvich, 1981). The effective sensitivity of the S cones, for example, will be reduced in the presence of short-wavelength radiation. These adaptive processes may well partly explain the phenomenon of colour constancy whereby it is believed that surfaces tend to maintain their approximate daylight appearance when viewed under a wide range of light sources. Colour constancy is surprising, at least at first consideration, since when the spectral properties of the illumination are changed (such as when we take an object from one room to another) the spectral distribution of the light that reaches the eye from an illuminated object can change quite markedly and yet the colour of the object remains almost constant.

A further important process that occurs in the retina is that the responses of the cones are combined with each other to produce opponent signals (Kaiser and Boynton, 1996; Hurvich, 1981). The responses of the L and M
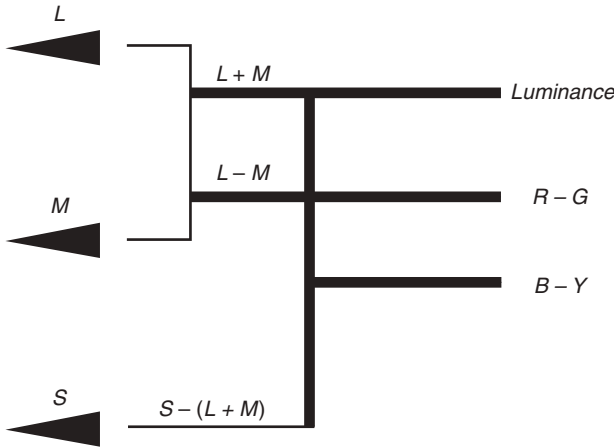
1.4 Schematic diagram to show how the cone responses may be combined to generate a luminance channel and two opponent chromatic channels.

cones are additively combined to produce a luminance signal and subtracted from each other to produce a red–green signal. A blue–yellow signal is generated by subtracting the *S* cone signal from the sum of the *L* and *M* signals. Possible anatomical linkages are schematically represented by Fig. 1.4.

Mathematically, we can express the opponent processing by equations such as:

$$Lum = L + M,$$

$$O_{RG} = L - M,$$

and

$$O_{BY} = S - (L + M)$$

where *Lum*, O_{RG} and O_{BY} represent the opponent signals and *L*, *M* and *S* represent the responses of the cones[5]. The principles of additive mixing and the choice of additive primaries may be explained by the principle of univariance and the spectral sensitivities of the cones (Westland, 2002). Other phenomena of colour vision, however, require an understanding of opponent processing to be explained. For example, although additive colour mixing and trichromacy lead to the view that there should be three

5 Note, however, that this is only one possible way of combining the cone responses. There still remains uncertainty, for example, as to whether the short-wave sensitive cones contribute to the luminance signal.

colour primaries, psychologically it has been long known that there are four colour primaries, red, green, yellow and blue (Wandell, 1995; Hurvich, 1981). The facts that redness and greenness are opposite sensations (that do not occur at the same time) and that similarly yellowness and blueness are opposite sensations, stem from the opponent processing in the retina. Anatomically, the opponent processing is carried out in the retina as the cone responses are combined, first by horizontal and bipolar cells, and finally by retinal ganglion cells (Bowmaker, 2002).

The retinal signals leave the retina and pass along the optic nerve away from the eye into the brain. The fibres from the two eyes meet and cross over at an anatomical structure known as the chiasma. The signals from the left-hand part of the visual field from both eyes project to the right hemisphere of the brain and those from the right-hand part of the visual field are processed in the left hemisphere. The retinal ganglion fibres terminate at the lateral geniculate nuclei or LGN (one LGN lies in the right hemisphere of the brain whereas the other lies in the left hemisphere), where a certain amount of further processing takes place, before long fibres known as optic radiations take the signals to an area in the lower rear (occipital) part of the cerebral cortex which is called the visual cortex.

1.4.3 Spatial vision

It is important to understand that colour vision and spatial vision are inextricably linked. Invariably, when we observe a colour stimulus it is in the context of a surround and/or background (Hurlbert, 2002). In Fig. 1.5, for example, two physically identical grey-square stimuli do not have the same appearance because of their different backgrounds. The spatial processing
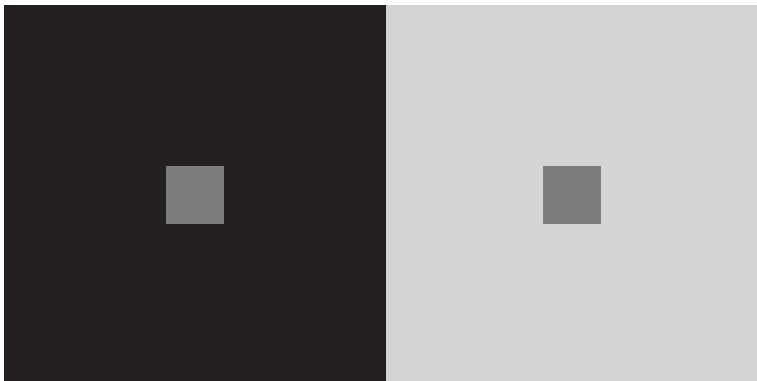
1.5 The two small grey squares are physically identical but do not have the same appearance because they are displayed against different backgrounds.

Excitation

+

−

Inhibition

+   −

Top view

+

−   −

Side view
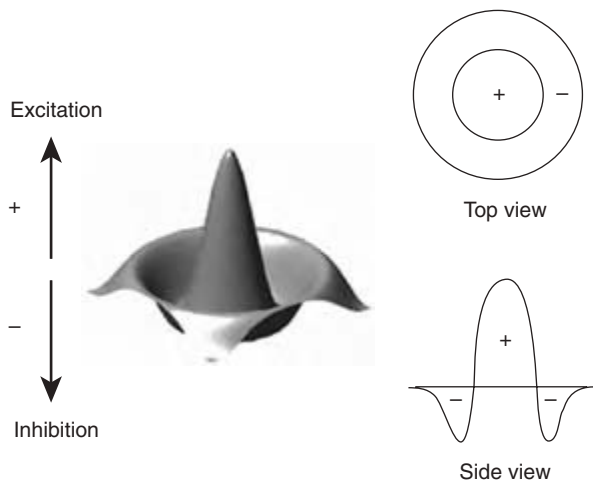
1.6 Three different representations of the spatially opponent receptive fields of a retinal ganglion cell.

that takes place in the human visual system therefore impacts upon how colour perception operates.

That many retinal ganglion cells are spectrally opponent has already been introduced in the context of colour opponency. However, most opponent cells are also spatially opponent (Bartleson, 1984). The concept of spatial opponency is best explained in terms of receptive fields. The receptive field of a cell is the part of the visual field that influences the response of that cell. The receptive fields of retinal ganglion cells are quite large and this is because many cone cells contribute to the response of each ganglion cell. A given ganglion cell may be excited to respond by some cone cells and inhibited by others[6]. Typically, the pattern of excitatory and inhibitory connections of cones to a ganglion cell may cause the ganglion cell to be excited by an increase in light intensity in the centre of its receptive field but inhibited by an increase in light intensity at the periphery of its receptive field (Fig. 1.6).

The spatial opponency of many retinal ganglion cells is undoubtedly the physiological basis for simultaneous-contrast effects such as that illustrated by Fig. 1.5. It also explains why the visual system is more sensitive to contrast in a scene rather than to absolute light intensity.

6 If a cone cell excites the ganglion cell then it means that a strong response of the cone cell causes a strong response of the ganglion cell. Conversely, cone cells that inhibit the ganglion cells cause the ganglion-cell response to reduce as the cone-cell response increases.

There is overwhelming evidence that the visual system performs a multiresolution analysis (in parallel) of images (Cambell and Robson, 1968; Wandell, 1995). What this means is that the visual system encodes multiple representations of an image for different colour directions (e.g. luminance, red–green, blue–yellow), spatial frequencies and temporal frequencies. The spatial-frequency response of the visual system as a whole can be quantified by the contrast-sensitivity function (CSF) (Campbell and Green, 1965). The CSF records the sensitivity of the three colour channels to contrast for gratings of varying spatial frequency. Measurements of CSF for the luminance channel show, for example, that the visual system is more sensitive to pattern (corresponding to a spatial frequency of about six cycles per degree of visual angle) than it is to spatially uniform fields[7]. For further details of the retinal and cortical processes and the interactions between colour vision, spatial vision and motion readers are directed to other sources (Wandell, 1995).

1.5   Colour perception

Colour perception for humans is three-dimensional, a fact that almost certainly stems from the existence in the retina of three different classes of light-receptive cells. Three terms, or numbers, are necessary and sufficient to define a colour stimulus for the visual system under standard conditions (Westland and Ripamonti, 2004). For example, we might describe a colour by its hue, its colourfulness and its brightness or we might specify a stimulus by the *XYZ* tristimulus values of the CIE system. It is important to note, however, that colour is only one aspect of total appearance for surfaces in the world and many other phenomena contribute to overall appearance, including gloss and texture. Furthermore, the complex nature of colour perception means that it is impossible to predict even the approximate colour appearance of a patch in a scene without specifying the surrounding colours and the state of adaptation of the eye.

1.5.1 Colour contrast

The three-dimensional nature of colour may be explained by trichromacy and the existence of the *L*-, *M*-, and *S*-cone types but the notion of spatial colour contrast is essential to a modern understanding of colour perception. Figure 1.5 illustrates an example of lightness contrast, but the same type of

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7 The luminance CSF is said to be band-pass in shape; that is the luminance channel has maximum sensitivity to contrast at about 6 cyc/deg and reduced sensitivity for increasing or decreasing spatial frequencies. The chromatic CSFs have been rather less-well studied but are believed to be low-pass.

phenomenon occurs for colour stimuli. Thus, a yellow patch viewed on a green background will appear more reddish than the same physical yellow patch on a red background. The simultaneous contrast effect illustrated in Fig. 1.5 can also be demonstrated temporally as successive contrast or after-images. We often notice these contrast effects when we are presented with contrived displays such as Fig. 1.5, but both spatial and temporal contrasts are continually operative in our visual field during normal visual tasks. The colour appearance of a patch in a scene is dependent upon the context (both spatial and temporal) in which the patch is observed. A thorough review of spatial and contrast aspects of colour vision is provided by Hurlbert (2002). For certain stimuli, the colour of a patch takes on the hue of the surrounding background rather than contrasting with it and this effect is known as colour assimilation (Ripamonti and Gerbino, 2001). Since the effects of contrast and assimilation are not yet entirely understood, it is difficult to predict colour appearance and this issue is discussed in the following two sections.

1.5.2 Colour constancy

Spatial colour contrast effects can cause otherwise physically identical colour stimuli not to have the same colour appearance. Similarly, physically disparate stimuli under certain circumstances can have the same appearance. This latter phenomenon is one consequence of colour constancy, one of the great mysteries of colour vision. How is it that our colour perception of surfaces in the world remains approximately constant as we move from a bright scene to a dimly lit scene and even from a room illuminated by one coloured light source to a light source of another colour? The phenomenon of colour constancy is a critical functional component of our colour vision because it enables us to discount changes in the light source and so recognise objects in the world by their colour. It is surprising, nonetheless, because the changes in the colour signal (the spectral power distribution that results when an object is illuminated by a light source), which occur when we change the illumination, can be substantial and therefore would not seem trivial to discount. For example, the absolute intensity of the light reflected by a black object outdoors on a sunny day may be greater than the intensity of the light reflected by a white object in a dimly lit room, but the objects appear black and white, respectively, under both illumination conditions.

A number of approaches have been proposed for the way in which the visual system can discount the effect of the illumination (Finlayson, Drew and Funt, 1994; Hurlbert, 2002; Foster, 2003). The retinal process of chromatic adaptation may play a role in enabling colour constancy, since a consequence of this process is that the spatial-average output of a cone class

is likely to be similar regardless of the colour of the illumination. However, some researchers argue that chromatic adaptation and colour constancy are entirely different phenomena (Brill and West, 1986). Chromatic adaptation requires several seconds to occur whereas colour constancy tends to take place immediately (Land, 1986). Secondly, chromatic adaptation can occur for simple stimuli, whereas colour constancy works best for so-called complex images where there are many different surfaces in the scene (Hurlbert, 2002).

Since it seems clear that chromatic adaptation cannot entirely account for the phenomenon of colour constancy, some computational models try to recover the spectral reflectance of the surfaces in a scene from the triplets of cone responses that they elicit (Maloney and Wandell, 1986). Other approaches propose that colour constancy may be achieved by using the information contained in highlights produced by specular reflection from glossy surfaces (Hurlbert, 2002). The highlights contain the same relative spectral power distribution as the light source and therefore may provide a clue to the colour of the light source. However, most successful approaches to explain colour constancy incorporate the fact that the colour appearance of a patch in a scene is relative to that of other patches in the scene (Land, 1986).

1.5.3 Colour appearance

The phenomena of colour contrast and colour constancy are both aspects of colour appearance. For many industrial applications colour appearance is strictly not an issue. For example, if a manufacturer wishes to determine whether two batches of paint are the same colour, he could measure the CIE tristimulus values for a sample of each of the two paints. If the two samples have the same CIE XYZ values, the manufacturer would be able to state with confidence that, for the average observer[8], the two samples would look the same colour as each other. However, this match would be conditional upon a given illumination, viewing distance, sample size, background, etc. A spectral match (where the spectral reflectance factors of the two paints were identical) would give greater confidence that the two batches of paint would look the same, but such a match would still be conditional on the paint samples being viewed against the same background as each other. Neither the spectral reflectance values nor the CIE tristimulus values, however, would give much useful information as to what colour the

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8 Strictly, the manufacturer would only be able to claim a match for the CIE standard observer. Since the CIE standard observer was the result of visual assessments made by a very small number of people, it is unlikely that the CIE standard observer is equal to the average observer.

paint samples would actually appear to be for any given observer under any set of conditions.

It has been shown that colour appearance is a complex phenomenon, and a deep understanding of the properties and function of the human visual system is required in order to appreciate it. Some advances in predicting colour appearance have been made. For example, the CIELAB system can be described as a colour-appearance model although it is not a particularly effective one. So, for example, a neutral achromatic object will have CIELAB coordinates ($a^*=b^*=0$) that do not change with the illuminant. Furthermore, recent progress has been made in the form of sophisticated colour-appearance models such as CIECAM97s (Li, Luo and Hunt, 2000) and CMCCAM2000 (Li *et al.*, 2002). Unfortunately, whilst such models are useful for certain practical and well-defined situations, further research is required before such models even begin to be able to account for the majority of visual phenomena. Ultimately, our perception of colour may forever remain a private experience.

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