1

The Perception of Colour

1.1 Introduction

Before addressing the reproduction of colour it is essential to have firmly based ideas about what colour is, its spectral characteristics, the way it is described differently by different people and the importance of a common naming nomenclature. Thus this chapter describes how colour is perceived, and how it is unambiguously characterised, both in terms of the quantitative and qualitative responses it evokes in the eye.

The sensitive elements of the eye at normal levels of illumination are identified and characterised both in terms of their overall sensitivity and in terms of their spectral responses.

1.2 Setting the Scene

To introduce colour as a subject for study immediately presents one with a problem. In contrast to other subjects we may decide to investigate, we all have preconceptions as to what colour is. We think we already know much about colour, we have experienced it from early childhood, colour names crop up in speech on a regular basis, we have probably been taught at school how to mix colours to obtain a wider range than those available in the paint box and almost certainly at some stage we have been introduced to the concept of primary colours as the basis of obtaining a wide range of colours from the mixture in varying amounts of just three distinctly different primary hues. We will be formally defining the parameters which are used to describe the various aspects of colour later. For the present, however, the *hue* of a colour describes whether it is, for example, green, yellow or violet.

However the manner in which we perceive colour, though at an overview level not particularly complex, is just complex enough to require a level of attention beyond that which many of us have been prepared to give on a casual basis. Experience has shown that as a result there is widespread confusion about how colour is perceived.

One of the problems associated with initial considerations of colour perception is the naming of colours and the manner in which we differentiate colours of various hues through the spectrum. The following four paragraphs on *unitary hues* adapted from the work of Ray Knight provide a sound basis on which to commence consideration of this topic.

Colour Reproduction in Electronic Imaging Systems: Photography, Television, Cinematography, First Edition. Michael S Tooms.

Companion Website: www.wiley.com/go/toomscolour

As we step through the visible spectrum from red to violet we pass a considerable number of quite distinct hues. A listing might read as: red, orange, yellow, green, cyan or turquoise, blue and violet. (Purple and magenta hues do not appear in the spectrum.) Because these seven colours continuously blend into each other we perceive many more than these seven hues, and certainly more hues than we have distinct colour names to identify them with.

Of the seven fundamental colours named above, only four are truly distinct and to these we can add black and white which together make up a group called *psychological colours* or, when hues only are being referred to, as *unitary hues,* attributed to Ewald Hering (1834–1918), which are red, yellow, green and blue. These four important colours, share the distinction that each one can be described without reference to the other three, or any other colour. Consider yellow, for example. To find a pure yellow without a hint of either adjacent colour means we look for a yellow with an absence of green and an absence of red – perhaps chrome yellow. Such a hue can be found, but not so with orange or purple and some other hues. Orange has within it an element of yellowness and redness, and purple has elements of blueness and redness.

This unambiguous isolation of hue only happens with the four unitary hues. It is quite fundamental that this occurs and is a matter of course without any teaching or learning.

The fact that some colours can be described by reference to their adjacent colours in the colour wheel, such as blue-green, means that the colour – just described – is *not* one of the four unitary hues of red, yellow, green or blue; if we mix blue and green the mixture is called blue-green, turquoise or cyan, and to confuse the situation, sometimes just a blue or green. Thus cyan is a hue with a blueness and a greenness about it which creates a colour naming problem, quite apart from the fact that this hue is not differentiated from blue or green in some cultures. So it is also for purple between red and blue; orange between red and yellow, and lime or yellow-green between yellow and green.

Thus one of the causes of the confusion alluded to above, is the predilection of many people, often men, to describe colours as variants of these unitary hues, red, yellow, blue and green, without differentiating them even into some of the other principal hues we experience such as orange, turquoise, violet and magenta, for example. One serious outcome of this casualness in describing principal hues has led to a common misconception that the so-called primary colours are red, yellow and blue. The author has had to face the almost impossible task, on more than one occasion, of persuading a young relative that their teacher was wrong in using these colours to describe the primary hues.

Returning to the complexities of colour perception, unless one understands the underlying rationale of what is going on, it is all too easy to become confused when faced with the prospect of one set of primaries for the mixing of coloured lights and a different complementary set for the mixing of pigments of various types. However neither set is the red, yellow and blue set referred to above. We will be looking further into what we mean by primary colours in Chapter 2.

All around us are examples of incorrect colour naming; take for example Robin Redbreast, so described, it would seem, to achieve an alliteration; in fact even a casual glance at a robin shows it to have an orange breast.

One might reasonably ask at this stage how we can be sure that we all perceive a particular colour in the same way. Early experiments, which we will be looking at in some detail later, showed quite clearly that those with normal vision do perceive colour in broadly the same way. There are of course people with defective colour vision; this does not mean they see in monochrome but usually one of the three colour receptors in the eye is defective to a degree, which leads to them being unable to differentiate between colours within a certain range of colours in the spectrum. In broad terms, some 8% of males are colour defective to a degree whilst for females the figure is only in the order of 1%. Total colour blindness is exceedingly rare.

Even for those prepared to differentiate between colours of vaguely similar hue and saturation there can be differences of opinion as to the naming of colours. Saturation is the term used to describe the intensity of a colour, adding white to a colour makes it increasingly desaturated. The situation is complicated further when we take the lightness and darkness of colours into account, many different words are used to describe the various parameters of a colour, and sometimes the words used are inappropriate and often are just wrong. Frequently for example, 'shade' is used to describe the hue of a colour which is only slightly different from the hue of another colour with which it is being compared. We will formally define the various terms used to describe colour a little later when some of the fundamentals of the manner in which we perceive it have been reviewed.

Though many readers who have picked up this book will not be amongst those used in the examples above, nevertheless in the author's experience there are sufficient readers who would benefit from a review of the way we perceive and describe colour before moving on to the more formal approach of the manner in which we measure colour in Chapter 3.

1.2.1 The Historic Developments Leading to an Understanding of Colour Perception

Already we take much for granted; it is difficult to put oneself in the position of someone attempting to grasp colour in the era before Newton. It was he who first showed that using a

Figure 1.1 Splitting and recombining white light with a prism and a lens respectively.

small hole cut into his window blind to enable a shaft of sunlight to fall onto a prism, white light could not only be dispersed into the colours of the spectrum but also by using a convex lens, the spectrum colours could be recombined to reproduce the white light once more as illustrated diagrammatically in Figure 1.1.

1.2.1.1 Naming the Spectrum Colours

The traditional way of looking at a spectrum is to use a prism and a narrow slit with a source of white light, either the sun or a tungsten lamp, to display the spectrum on to a sheet of white paper. More conveniently in this era of computer disks, one can hold a CD at an appropriate angle to a bright tungsten light source to see the spectrum directly.

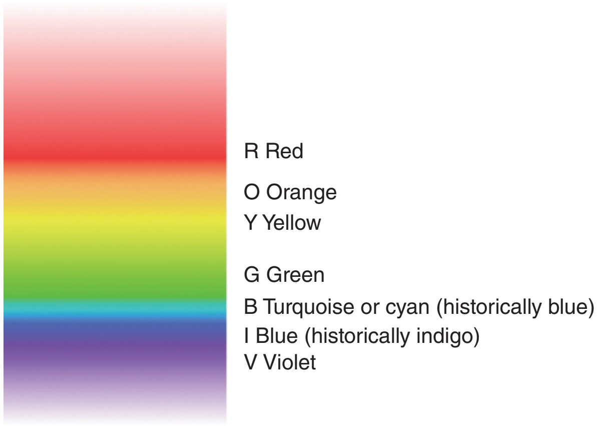

Figure 1.2 Colour naming the spectrum.

In doing so one obtains a range of colours which may be named as shown in Figure 1.2

The capital letters represent those of that old mnemonic to remember the spectrum colours: Richard Of York Gained Battles In Vain. The names of the colours as we are presently more inclined to use them have been added, together with their historical names for reference. Already one begins to see the opportunities for ambiguity.

Generally there is little ambiguity in naming the colours between red and green and these colours appear subjectively pretty much as one would expect. However between green and violet the situation is subjectively not so clear cut.

The colour most of us would perceive as turquoise, or cyan as it tends to be called in colour discussions, that is a colour subjectively perceived as half way between green and blue, occupies only a very narrow band of the spectrum between green and blue and is difficult to pick out within a continuous spectrum. In spectral terms most of that area of the band is taken up with a colour which many of us would describe as light blue. True blue, that is, the blue we describe as ‘primary blue’, occurs only briefly between cyan and violet. The spacing of the colours in the spectrum depends on whether the spectrum is generated by a prism or a diffraction grating.

Indigo is really an old name for a colour which is close to primary or ‘true’ blue. Unfortunately the use of current colour names prevents us falling back on that old mnemonic to remember the spectrum colours. The old names are included for reference. It is interesting to note that several well-recognised colours such as brown, pink, purple and magenta are not represented in the spectrum.

In discussing *colour* in terms of reproduction we generally take its most comprehensive meaning which embraces all colours of the same or similar hue, including those with ever diminishing levels of saturation as one approaches the neutral or grey tones between black and white. (A neutral white or grey surface colour is one which reflects equally at all wavelengths of light.) True there are exceptions, particular amongst those colours between red and violet where different levels of saturation lead to different names, the most common example being desaturated red which is universally known as pink.

1.2.2 Surface Colours

So, being aware that white light is actually a combination of all of the colours in the spectrum it becomes easier to appreciate that when it falls upon a surface the resulting colour we see is a mixture of all the colours reflected by the surface. If all colours are reflected we see a white surface but if some colours are absorbed, we see a colour which results from the *mixture of the colours of the spectrum which are reflected.*

Standard tiles with specified spectral reflection characteristics are available and samples from the range of Lucideon[1] standard tiles are illustrated in Figure 1.3.

Figure 1.3 Samples from the Lucideon range of standard tiles.

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[1] Tiles are very colour fast and therefore are a very useful media for producing ranges of test colours. Lucideon is a company previously named CERAM, which specialises in producing tiles with specific reflection characteristics for use as standards within the industry. http://www.ceram.com/materials-development/colour-standards. The tiles are supplied by Avian Technologies in the United States; see http://www.aviantechnologies.com/products/standards/reflect.php#ceram.

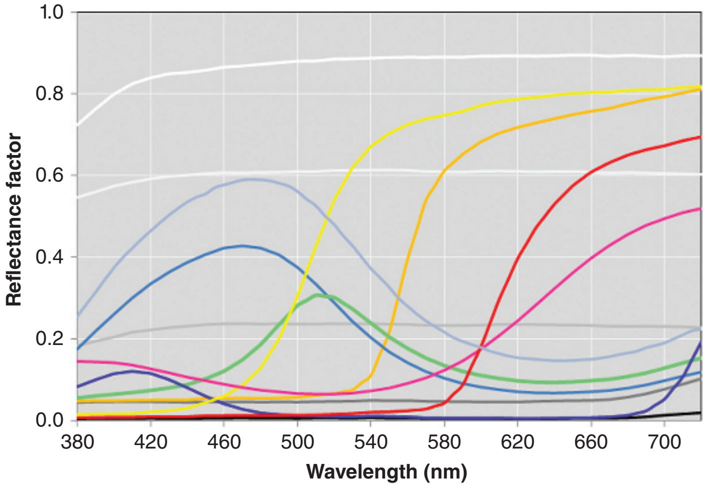

Figure 1.4 Reflectance characteristics of samples from the Lucideon CERAM range of test tiles.

> In Figure 1.4 the spectral reflectance characteristics of a set of ceramic test tiles from the Lucideon range are illustrated. The colours of the curves are an approximate indication of the colour of the surfaces they represent. Note how the white tile reflects nearly 90% of the light across most of the whole of the colour spectrum, whilst the colour of the yellow tile is comprised of the light of the spectrum colours, green, yellow, orange and red.

The reader may wish to return to this graph once the information in the remainder of this chapter has been noted in order to review how the absorption of the light in certain spectral bands dictates the perceived colour of the surface. Ceramic test tiles are extremely colour stable and we shall be using the characteristics of this Lucideon range in subsequent chapters of this book.

We are now getting into the detail of what colours we see when certain parts of the spectrum are missing. We know that when the eye is exposed to a spectrum comprising broadly equal amounts of light from violet to red, we perceive the colour white; but in order to be able to predict what we see when a combination of elements of the spectrum are present, we need to investigate how the eye–brain complex responds to mixtures of elements of the spectrum. To do this we need to characterise in some detail how the eye responds to light of differing levels and to light of various frequencies or wavelengths within the spectrum.

1.3 Characterising the Responses of the Eye to Light

Colour is the term we use to describe how the eye perceives light of varying strength at different wavelengths, and light may be defined as the energy in that segment of the electromagnetic spectrum to which the eye responds. The electromagnetic spectrum in its entirety is extremely broad and comprises with increasing frequency: radio, infrared, light, ultraviolet, x-rays and gamma rays. In many branches of science and engineering electromagnetic energy is discussed in terms of frequency whilst in others it is in terms of wavelength. Wavelength and frequency of light are inversely related by the speed of light such that the wavelength 'λ' (lambda) equals the speed of light 'c' divided by the frequency 'f' in cycles per second.[2]

$$\lambda = c/f$$

where $c = 2.99792458 \times 10^8$ m/s or very nearly 3×10^8 m/s.

In treating the subject of light and colour the general practice is to refer to light of a given wavelength rather than to its frequency and to a band of wavelengths as a spectrum.

The eye perceives colour as a characteristic of light. Light is formally that very narrow segment of the electromagnetic energy spectrum occupying wavelengths of approximately 380–720 nm. (A nanometre or nm is one thousand millionth of a metre or 10^{-9} m). It is interesting to speculate on how we evolved such that our eyes are sensitive to just that part of the electromagnetic spectrum where the constituent molecules of surfaces are of such a range of dimensions that their interaction with electromagnetic energy allows light to be differentially absorbed or reflected across the visible spectrum.

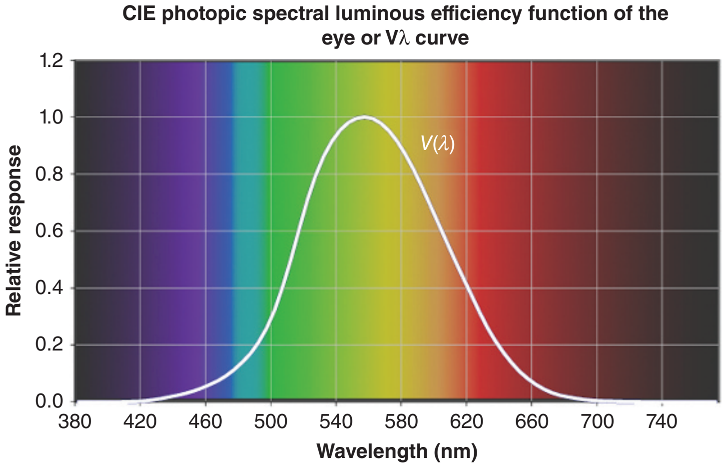

Figure 1.5 Spectral sensitivity of the normal human eye.

In Figure 1.5, the varying sensitivity of the eye over the segment of the electromagnetic energy spectrum to which it is sensitive is illustrated and is known formally as the CIE[3] Photopic Spectral Luminous Efficiency Function but often referred to in its abbreviated form as the 'luminous efficiency function' or in shorthand as the $V(\lambda)$ curve (pronounced the 'V lambda' curve). In the figure it is superimposed over a faint version of the spectrum to give an indication of the relationship between the spectrum colours, the wavelengths of light and the relative response of the eye. This curve, often also referred to historically as the photopic response of the eye or the luminosity function, is the average response of a large number of people with normal colour vision and correspondingly with very similar response curves. We will often use the '$V(\lambda)$ curve' as a recognised short hand in references to this function throughout this book. More recent work has shown the response to be very slightly uplifted on what is illustrated between about 380 nm and 450 nm[4] but nevertheless this is a CIE

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[2] The unit of a cycle per second is the Hertz, named after the German physicist Heinrich Hertz who proved the existence of the electromagnetic waves theorised by James Clark Maxwell.

[3] Commission Internationale de l'Eclairage or International Commission on Illumination

[4] http://en.wikipedia.org/wiki/Luminosity_function

standardised response and as such is still used for all day-to-day luminous intensity and colour measurement work. You will note that the response is limited to roughly 400–700 nm and peaks at 555 nm in the yellow-green area of the spectrum.

The sensitive cells in the retina of the eye responsible for producing a sensation from the stimulus of light are comprised of two principal types to provide the ability to respond to a very wide range of the level of light perceived. The cones are responsible for *photopic* vision under normal levels of illumination, from bright sunlight down to low levels at dusk, and the rods are responsible for *scotopic* vision at very low levels of illumination, represented by moonlight, for example. Scotopic vision is monochromatic, in that colours cannot be determined; however, there is an overlap range of low-level illumination where both types of receptor are effective, which is described as *mesopic* vision. The remainder of this book will, unless specifically indicated otherwise, always relate to photopic vision.

1.4 The Three Characteristics of the Eye Relevant to Reproduction

The eye is sensitive to the quantity, quality and spatial distribution of the light it perceives. It is convenient initially to deal with the quantitative and qualitative responses of the eye separately before finally considering both of these aspects together.

- Quantitative response. How the eye responds to the amount of light. The accommodation of the eye to a wide range of levels of illumination; the lightness and tonal aspects of colours.
- Qualitative response. How the eye responds to the quality of the light, that is, how light energy of differing spectral content influences how we perceive the light in terms of its hue and saturation, or when these terms are taken together, its chromaticity. These terms are defined later in this chapter.
- Spatial response or acuity of the eye. The ability of the eye to resolve detail differs for changes in lightness and in colour. The relevance of these differences in acuity to reproduction will be addressed in Chapter 14.

1.5 The Quantitative Response or Tonal Range of the Eye

The ability of the eye to operate over a wide range of illumination is truly remarkable. In bright sunlight the illumination level may be between about 50,000 and 100,000 lx, whilst moonlight produces a peak of only about 10 mlx (millilux or 10^{-3} lx). Lux is a measure of the intensity of illumination and one lux is formally defined as equal to one lumen per square metre. The luminance of a surface reflecting light is measured in terms of nits[5] or cd/m^2. The derivation and use of photometric units together with their relationship to physical units is addressed in Appendix A.

This range encompasses both photopic and scotopic vision. Very broadly the vision ranges may be categorised as follows:

- Photopic vision covers the range of luminance greater than 10 nits or cd/m^2
- Mesopic vision covers the range of luminance between 10 mnit and 10 nits
- Scotopic vision covers the range of luminance less than 10 mnit

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[5] See Appendix A. Using nits rather than cd/m^2 is more efficient, in the same way as we use amps or A to describe electric current rather than using coulomb per second or C/s.

However, we are unable to embrace this very large range of luminance in a single scene; the eye rapidly adapts to the lightest surface of significant image area in a scene; where 'rapidly' is a comparative description. We barely notice day to day changes of illumination when moving from an internal to external environment, even though the level of illumination may change in the order of 100:1 but we are probably familiar with wartime stories where the observers on ships, when moving from a dimly lit interior, required some 20 minutes to fully adapt to the outside dark conditions at night.

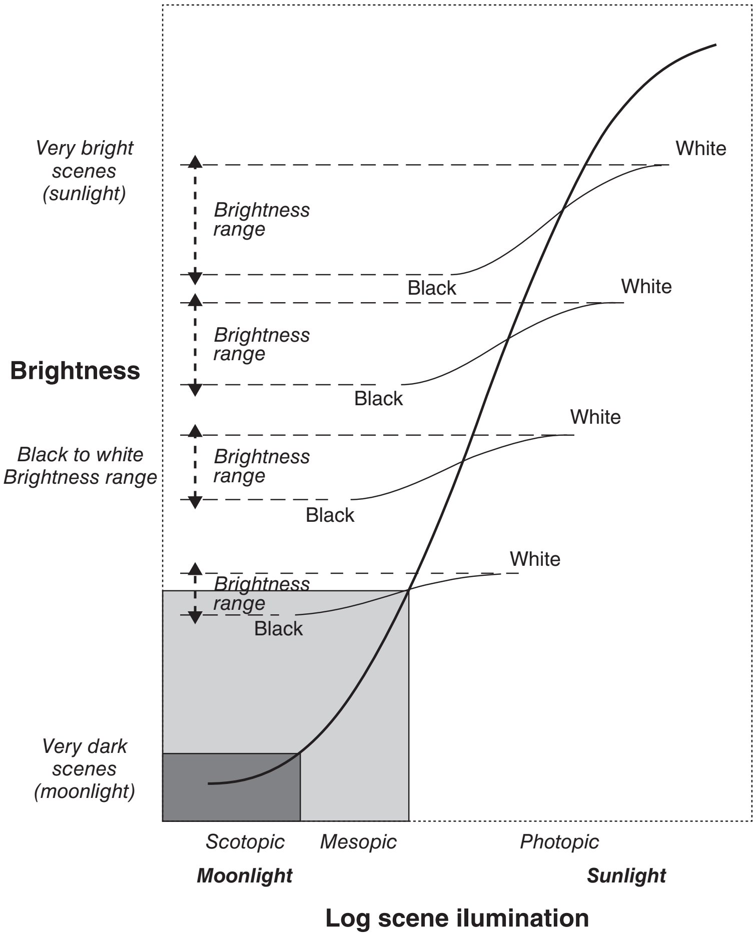

Figure 1.6 The response of the eye to increasing levels of illumination.

In Figure 1.6 the adaptation of the eye to a wide range of scene illumination is shown, indicating the relatively small range of perceived black to white sensation, or contrast range, that occurs at every level of adaptation.

This informative curve was drawn by Ray Knight to illustrate the data derived by Marshall and Talbot (1942).

In all, the eye has a response range of about a billion to one. However, it cannot of course see this enormous range at the same time. The eye adapts to the brightness of the scene and for any given brightness the visible contrast range is limited – as shown by the reduced contrast range curves crossing the main curve at various levels of illumination. It is interesting to note that not only does the contrast range increase with increasing levels of illumination but also the steepness of the curves increases, indicating a greater perceived change in brightness with change in illumination. This is one of the primary reasons scenes ‘look better’ at higher levels of illumination.

If we take one of the adaptation curves towards the top of the range as representing an outdoor scene on a bright day and expand it to fill a graph we obtain a representation of the range of brightness the eye can respond to for a level of illumination represented by sunlight.

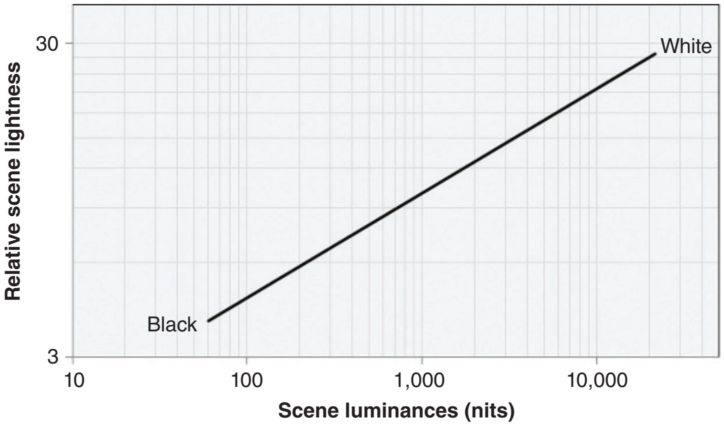

Figure 1.7 Response of the eye to an averagely illuminated scene.

Figure 1.7 is a log/log plot and in this case, we have chosen a level of illumination representing bright sunlight and a scene which contains light surfaces and deep shadows. The brightness of a scene, or more objectively the luminance of the various surfaces comprising a scene, is plotted in nits or candela per square metre of reflected light.

The relationship between scene illumination E in lux and the luminance of the scene L in nits (nt) or candela/m^2 (cd/m^2) is given by:

$$L = \rho E/\pi \, nt$$

where ρ is the reflection factor of a surface in the scene.

Thus taking a typical outdoor scene illuminated by the sun, the level of illumination may be about 75,000 lx, and the brightest surfaces may have a reflection factor of 0.90. Thus the luminance of the brightest surface in the scene, which will normally correspond to white, will be

$$L = 0.90 \times 75{,}000/3.14 = 21.5 \, knt$$

A log/log plot is chosen because the response of the eye in simplistic terms tends towards being logarithmic.[6] For the mathematically inclined, as we shall see in more detail later, the subjective response is roughly proportional to the cube root of the luminance of a surface, that is, L to the power of one-third. Such responses are produced as a straight line on log/log graph paper, as above. This subjective response to the relative level of light reflected from a surface, in comparison to the white of that surface, is referred to as the *lightness* of a surface.

The y axis gives the response of the eye in terms of the lightness of various elements of the scene or the tones in the scene from black through various less dark shades such as the dark greys, the browns and the blues to the lighter tones or tints such as the pale greys, the yellows and the pinks, for example.

The important factor to note is that the eye is much more responsive to small changes in the dark areas of a scene than similar changes in the lighter elements of the scene. Specifically it does not perceive a series of equal steps in luminance as equal changes of lightness; however, equal *percentage* changes in luminance of two samples with widely different luminances will produce a roughly equivalent equal percentage change in lightness. Work undertaken by Fechner and Weber indicated that in broad terms, depending upon the surround conditions and the adaptation of the eye, one can just perceive a 1% change in scene brightness over the adapted contrast range of the eye. This ratio of $\Delta L/L$ equal to a constant is now universally known as Weber's law.

Furthermore, it can be seen that in this example the scene contrast range is limited to a ratio of about 20,000 nits to about 60 nits or about 350:1. However, the actual contrast range will depend very much upon the type of scene, a darkish scene containing only a limited area of high brightness will evoke a greater range of perception because the low average level of illumination will cause the eye to adapt to that level whilst still accommodating the brighter elements of the scene. It is generally assumed for average scenes that the contrast range of the eye is limited to about 100:1.

The brightness of a scene is directly related to the level of illumination of the scene but the surface of an object within the scene may appear at a different 'lightness' depending upon its relative luminance compared with the average luminance of the whole scene and in particular the luminance of its immediate surroundings. An object of a particular luminance will appear to have a higher level of lightness when surrounded by objects of generally lower luminance and a lower level when surrounded by objects of a generally higher level of luminance.

We will expand further on tonal response and how it is affected by viewing conditions when we come to discuss the tonal response of the reproduction system in Chapter 13.

1.6 The Qualitative Response of the Eye

In Figure 1.8 is the same response of the eye we saw earlier and again including the hues that the different wavelengths of light evoke in the eye. Generally of course a surface will reflect light across a significant segment of the light spectrum. When all the light from an even broad spectrum source is reflected then the eye perceives white or a neutral grey, so it is useful to

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[6] Also using logarithmic scales enables one to illustrate a much wider range of data than would be practical with a linear scale and furthermore one becomes familiar with the concept that a straight line on a logarithmic plot indicates a simple power law relationship between the parameters portrayed.

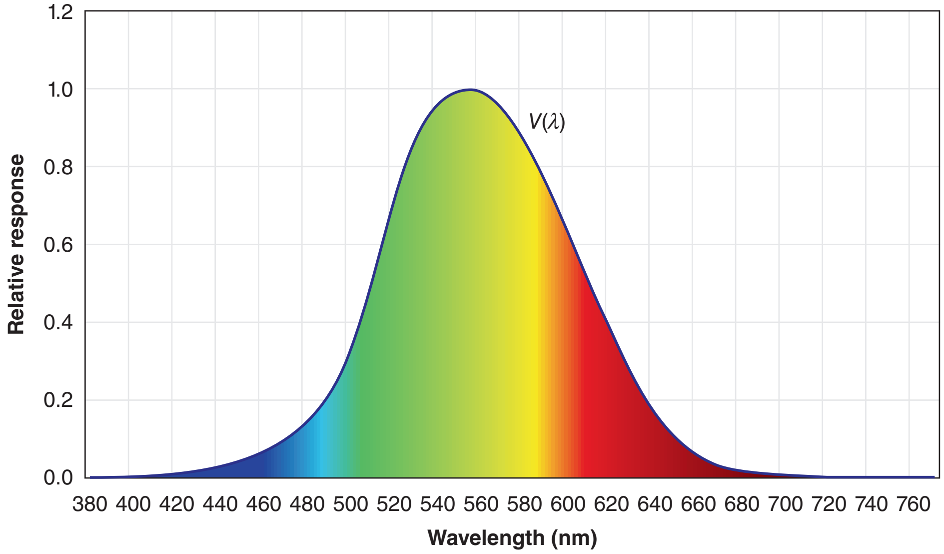

Figure 1.8 The response of the eye at different wavelengths.

consider that hues other than white appear only when the surface absorbs some of the incident white light. As noted earlier the response at the violet wavelengths has been shown to be slightly greater than illustrated here.

The spectrum starts with violet at below 400 nm, peaks at yellowish green at 555 nm and fades away again in the far reds above 700 nm.

If white light falls upon a prism, then we are all reasonably familiar with the coloured spectrum which is produced on a white surface placed to intercept the light leaving the prism, giving the spectrum colours shown earlier. As we have seen it is more useful to describe these colours using modern terminology to avoid the confusion which sometimes occurs when the colours are named by the names of the pigments which artists used centuries ago or even those names used by Newton who first created a spectrum with a prism.

Experiment shows that the addition of two lights of differing hues will evoke the response of a third colour in the eye. This gives a clue as to the mechanism by which the eye produces such an extraordinary range of colours in the brain. Early experiment indicated that the cones in the eye, which are the receptors responsible for vision at normal levels of illumination, were comprised of three types of receptors with very broad responses.

Unfortunately there is of course no direct way the spectral responses of the three types of receptors can be ascertained. Much work has been undertaken over the last 90 years or so by several workers based upon a number of different methods to establish the shape of these responses, including the work of Thomson and Wright (1947); Stiles (1978) and Estévez (1979). The results from each of these studies were similar enough to indicate they were at least representative of the actual responses. As we shall see later, knowing the actual shape of the curves is not critical to ensuring good colour reproduction since the method of measuring colour is not based upon a knowledge of these response shapes.

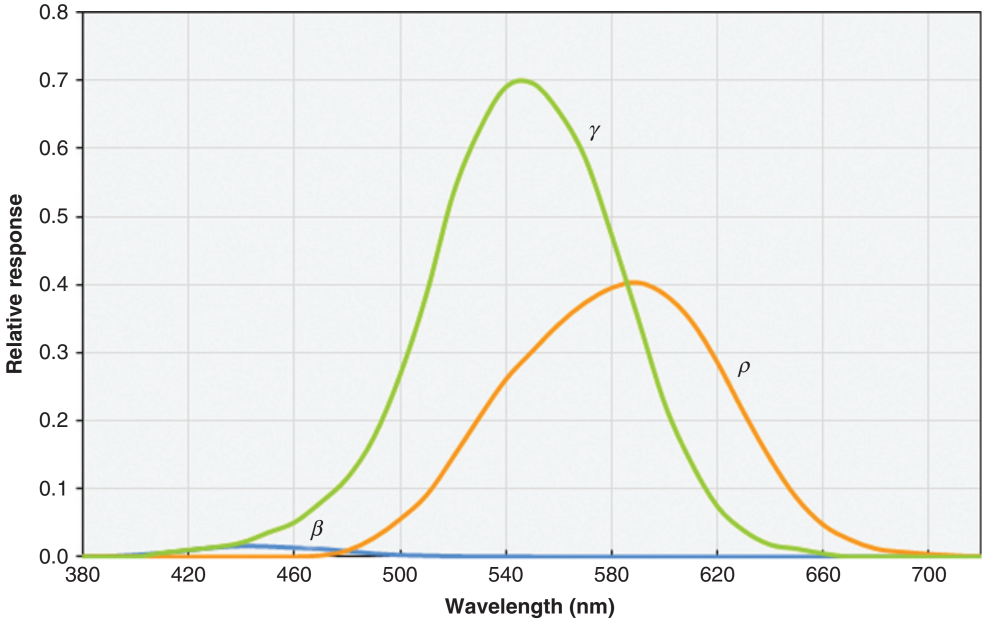

Figure 1.9 Spectral responses of the three cone receptors of the eye, derived from the work of Thomson & Wright.

> It is now generally accepted that the responses of the cones are similar to those illustrated in Figure 1.9, peaking at wavelengths corresponding to the blue-cyan, yellow-green and red-orange bands within the spectrum. These three cone response functions are designated the *beta* (β), *gamma* (γ) and *rho* (ρ) curves, respectively; also sometimes referred to in the literature as the S, M and L responses for short, medium and long wavelengths, respectively.
>
> Note the very low level of response of the beta receptor.

An indication that these three responses truly reflect the responses of the three types of cones may be ascertained by checking that the combined response of the three cone receptors equates to the luminous efficiency function of the eye.

> In colour work, the shape of the curves is usually more important than their relative sensitivities and the area under the curves of Figure 1.9 are each normalised to 100% in Figure 1.10 in order to enable the shape of the curves to be better appreciated. By normalised, we mean that the area under each of the three curves are made equal.

It should be noted that the precise shape of these curves is not known but since the accuracy in colour work is dependent upon the accuracy of the *measured* colour matching functions which derive from these curves, as shown in Chapter 2, this is of little importance to us.

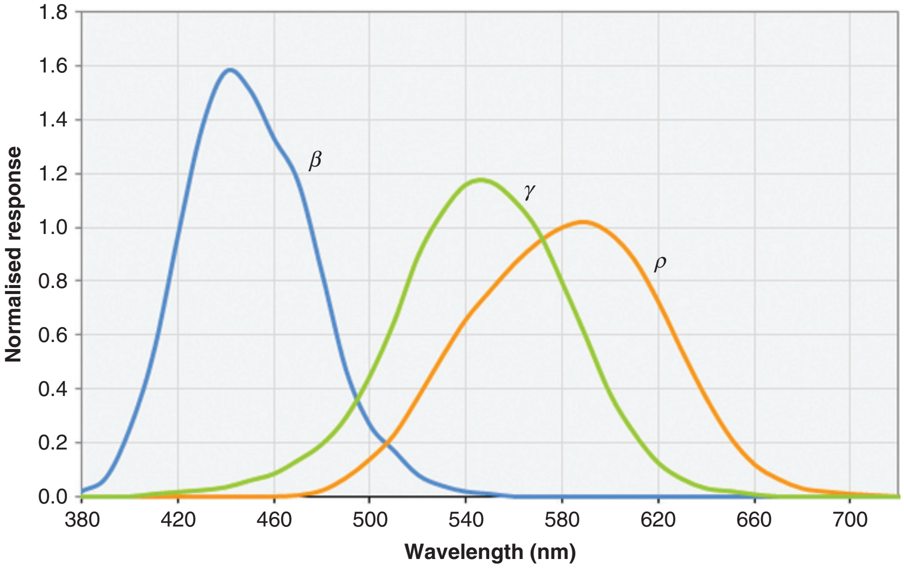

Figure 1.10 Normalised responses of the cone receptors of the eye, derived from the work of Thomson & Wright.

However, knowing the general shape of these curves is helpful in understanding the results obtained from appraising various aspects of colour.

The beta curve in particular has an extremely low comparative response and is shown here increased by a very large factor. (One can see that the peak of the beta curve at 445 nm relates to a response of the eye of only about 1% on the $V(\lambda)$ curve in Figure 1.8.) Although the beta receptor contributes very little to the luminance response of the eye, in colouring power terms it is of equal importance as the other two receptors.

As we shall see in later chapters, sufficient work has been undertaken to specify three colour matching functions relating to the measurement of colour and it follows from the method used to derive these functions that the data relating to the responses of the three cone receptors of the eye is contained within the data used to produce the standard colour matching functions. Thus the CIE, the international body responsible for standardising the colour matching functions, used these data to derive directly in both their 1997 and 2002 Colour Appearance Models (CIECAM97 and CIECAM02) (Hunt, 2004) the best match to the three receptors of the eye based upon the results of the workers listed above and several others responsible for more recent work. These calculations are undertaken in Worksheet 1 and illustrated in Figure 1.11.

As noted earlier, since the derivation of the $V(\lambda)$ curve, more recent work has indicated that the response between 380 nm and 500 nm is slightly higher than that indicated in Figure 1.8 and the evidence of violet at the extreme of the spectrum seems to point to this being due to the rho response falling to a minimum at around 460 nm but then recovering a little at shorter wavelengths. However, in order to ensure that full compatibility is retained between the $V(\lambda)$ curve and the sum of the cone response curves, for standardisation purposes the cone response curves continue to be derived with reference to the $V(\lambda)$ curve.

The eye–brain complex uses only the ratio of the levels of the signals from these three cone responses to evoke a specific visualised chromaticity, where chromaticity describes the

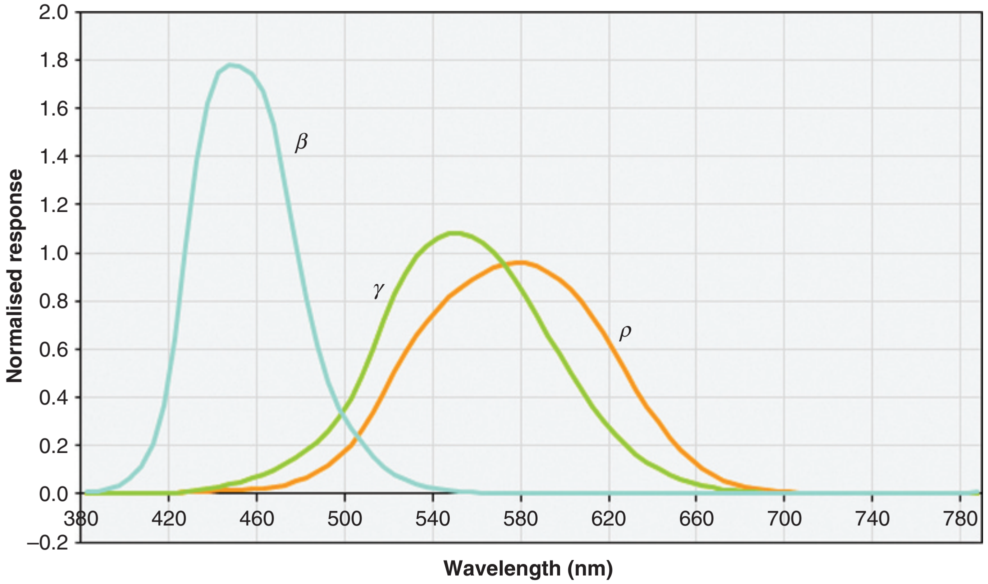

Figure 1.11 The CIECAM97 cone responses of the eye.

hue and saturation of a colour, usually shown plotted on a chromaticity triangle, circle or specific diagram (see Chapter 3). However, for a given level of adaptation of the eye, a colour with a defined spectral distribution may be described as orange for example at one level of illumination and brown at a lower level, even though the ratios of the responses in each of the receptors are identical. This explains how samples that may appear to be of a different colour may have identical chromaticities.

The above statement is so fundamental to the understanding both of what to expect from the mixing of colours and, as we shall see later, the fundamentals of colour reproduction that it is repeated to ensure that its importance has been fully appreciated:

The eye–brain complex uses only the ***ratios of the levels*** *of the signals from these three responses to evoke a specific visualised chromaticity*.

To be fully accurate, there are conditions where the visualised colour is also affected by other factors, such as colour adaptation but for colour reproduction this statement holds firm.

Note that all three responses are very broad and overlap and that the gamma and rho curves are relatively close together. If one were to produce optical filters with these characteristics and use them to view white light, then the beta light would be bluish; the gamma light yellowish green and the rho light an orangey red.