The modern approach to coloration

Introduction

With most textiles intended for the domestic market the attention of the purchaser is first arrested by their aesthetic appeal, and at that instant colour is often a persuasive factor. If the manufactured goods are of satisfactory quality they will conform to predetermined specifications appropriate to the intended use. Overall satisfaction therefore demands a design process capable of integrating both aesthetic and technical judgements, and it is in this area that the manufacturer realises the real worth of modern technology. Recently the accent on quality assurance and quality control has been underpinned by various technological developments. These have enabled producers to transform their organisations and production methods in their attempt to optimise costs, prevent the occurrence of defects, obtain a high degree of precision in predicting the performance of their goods and develop the necessary flexibility for a rapid response to the volatile demands of fashion.

Developments in most areas of activity in the coloration industry bear witness to the effective application of modern technology, starting in the colour kitchen where dyes and chemicals are dispensed and ending with delivery of customer service. For example, high-precision electronic balances make for a more accurate recipe composition where weighing is done manually. There are also facilities for dispensing dyebath chemicals through computerised control valves that have the ability to adjust the flow of dye liquor automatically from a large flow rate at the beginning of the dyeing cycle down to dropwise additions towards the end of the operation, where precision is most needed. This may be accompanied by automatic recording of the consumption of dye and chemicals for convenience in the administration of storage and purchasing.

Computer-aided design systems are more elaborate examples noted for their ability to produce digitised patterns from original artwork. There are also systems for textile printing that will either scan an image for reproduction or allow the creation of a free design, and translate the information into commands that initiate practical activities. Such a system is adapted to receive colour measurement information from a spectrophotometer that can be processed to provide a

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formulation for the colours needed. The set-up enables the user to maintain full control of the design input, design correction and colour formulation; the commercial reward is a drastic reduction in response time. Most computer-aided design units can be linked to colour printers that enable the coloured designs to be inspected on paper before starting production. In some cases the initial concept for the garment design is simulated on a three-dimensional model, and when this is complete it can be converted directly into the two-dimensional pattern corresponding to the shapes of the fabric pieces needed to make the garment. Simulation of the expected drape, the appearance of yarns or the effects of other construction details on the final garment may thus be assessed along with visual effects of any possible variations in colour. A similar principle can be applied to a carpeting contract. A three-dimensional presentation of the room layout can be prepared on-screen for the client's acceptance, and from this the area of carpet required is calculated directly.

In some arrangements the design can be analysed and a program produced automatically for direct transfer to either a computerised knitting machine or a loom. The possibilities are expanded further by the inclusion of a vast directory of colour to facilitate colour coordination or colour matching. This provides the manufacturer has the ability to reduce to one hour the time needed for a design operation that formerly would have required several days' work.

Parallel developments are to be found at different stages of the manufacturing process within the carpet industry. The capabilities range from the initial design process to simulation of the final appearance, thus enabling the contract carpet producers to illustrate the design to their clients in a variety of different colour combinations before starting manufacture.

Direct transfer of a pattern to the carpet coloration process has been accomplished through computerised control of spray nozzles or jets, the provision of which enables quick colour or pattern changes to be made without undue loss of production time.

Coloration processes have been at the forefront of many very successful applications of new technology to the overall design process. They are developments made possible by the advanced levels of theoretical insight, experimental methods and technology developed in various areas of textile and colour chemistry well before the advent of microprocessors. An outline of the background of colour measurement is therefore provided here to familiarise the reader with the relevant principles that have become embedded in everyday coloration practice.

Objective assessment of colour

At the end of the dyeing process judgements have to be made about the success achieved in matching the customer's required shade. Before embarking on the full-scale operation it was once the standard practice for past generations of dyers to reach the final shade via a range of laboratory trials to accommodate successive corrections in the dyebath formulation. During the trials the assessment of the corresponding changes in the appearance of the colour were recorded for future reference using verbal descriptions of the colour.

It has long been realised, however, that the human perception of colour is a physiological sensation that defies absolute verbal definition. Sir Isaac Newton during his investigations into the nature of light came to the same conclusion, and he held the belief that light is uncoloured but that each wavelength has the power to stimulate unique sensations in the brain. Nevertheless, in the past a methodical approach to the verbal expression of subjective colour assessment was the only means available for transmitting opinions about the appearance of colour; this is reflected in the nomenclature of commercial dyes (Chapter 4).

Describing colour

Changes in colour are expressed qualitatively through the use of the three variables hue, strength and brightness. *Hue* is defined as 'that attribute of colour whereby it is recognised as being predominantly red, green, blue, yellow, violet, etc.' [1]. Changes in hue therefore may result in the pattern being described as bluer, yellower, redder, greener, and so on. The term *strength* relates to the amount of colour present while *brightness* refers to the greyness of a colour.

The magnitude of any colour change may also be qualified using further terms such as 'trace', 'slight', 'little' or 'much' – for example, 'much redder', 'a trace bluer', and so on. Further aid to the visualisation of a colour is given by the designatory letters that follow the names of commercial dyes and by the provision of coloured samples in the dye makers' pattern cards.

Colour solid

Precision in the description of a colour is enhanced considerably by the organisation of colours in a three-dimensional array using lightness *L*, chroma (or saturation) *C* and hue *H*, as the coordinates describing a colour solid. Lightness is defined as 'that property of a coloured object which is judged

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to reflect or transmit a greater or smaller proportion of the incident light than another object', whilst chroma is 'the nearness of a colour in purity to the associated spectral colour (i.e. the sensation caused by monochromatic visible light of known wavelength)' [1].

The concept of a colour solid was first used by Munsell, and is represented diagrammatically in Figure 7.1, with the various hues contained by the perimeter of a circle. The lightness increases to white at the top end of a central vertical axis and decreases in ten steps to black at the bottom, the position of mid-grey coinciding with the centre of the solid. Colours falling on the same horizontal plane of the solid are of the same lightness.

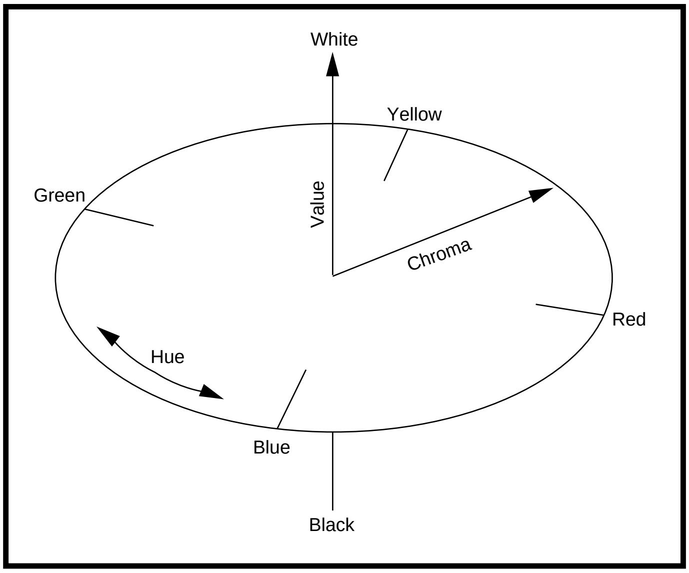

Figure 7.1 *The Munsell Colour Solid*

In any one plane the purity, or chroma, of the colour increases with increasing distance from the centre. Other names used as an alternative to 'chroma' have been 'saturation', 'purity', 'intensity' and 'vividness', but 'chroma' is the preferred term adopted by the colorant-using industries. The value ascribed to the chroma for white, greys and black is zero but the chroma of the perceived colour increases with movement towards the perimeter, where the most vivid or saturated versions of the spectral colours are placed. In practice each hue is represented on a page of a colour book or colour atlas (Plate 6). The lightness and chroma axes are calibrated using scale numbers, so that the spacing between successive units of chroma represents incremented changes of equal magnitude in visual appearance. Small coloured chips varying in lightness and chroma are prepared and positioned at the appropriate coordinates of each hue page. A complete visual colour atlas is formed in this way [2]. A representation of the Munsell coordinates and the corresponding hue qualifiers is given to illustrate the relationship between visual appearance and the corresponding verbal description in Figure 7.2, overleaf.

Although the Munsell chips provide a more objective way of describing colour, the level of precision they provide is still inadequate for denoting the location of a dyed textile in a colour space.

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Ultimate precision can only be attained with a system using continuously variable coordinates rather than stepwise scales.

There have been many efforts to develop a more suitable scale for the colour coordinates, and it is now possible to obtain a precise objective assessment of the extent to which trial dyeings differ from the required shade through instrumental measurements. This is a clear advantage and the replacement of verbal descriptions by unambiguous measurements has led to a significant improvement in the efficiency with which colours can be selected and matched to a customer’s request.

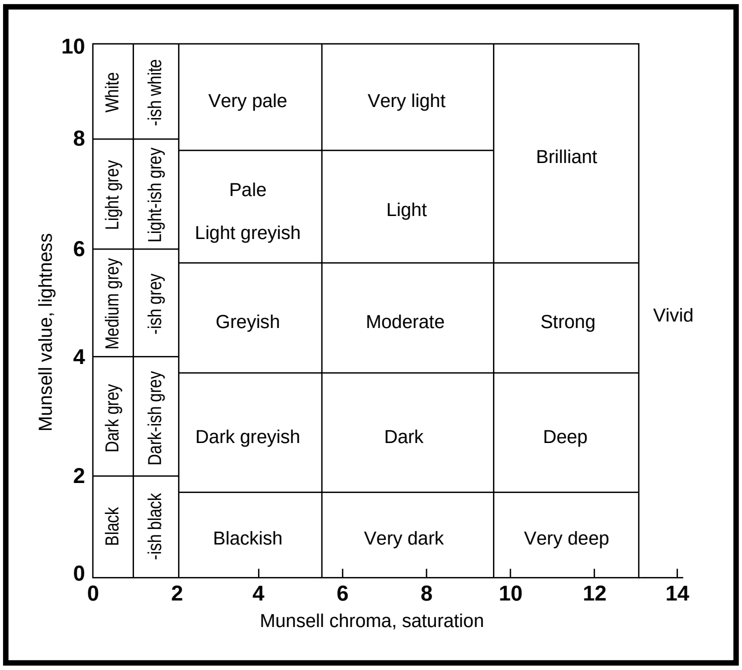

Figure 7.2 *Munsell coordinates and hue qualifiers*

ICI colour atlas

In 1970 ICI produced a colour atlas that enabled its customers to convert the colour of its patterns into colour coordinates. The values could then be transmitted to ICI and used by its Instrumental Match Prediction service to provide the customer with a suitable recipe. This form of colour atlas was constructed using the brightest hues, and a series of neutral-density filters were provided to place over the atlas to reproduce duller shades. This was equivalent to moving up and down the lightness/darkness axis of the colour space (Figure 7.1).

Development of such systems had become possible through an understanding of the nature of light and its interaction with dye molecules on the one hand, and application of the theoretical concepts concerning the human perception of colour to the design of colour-measuring instruments on the other. Accordingly the nature of light and the elementary principles of colour vision are described below to provide a background for later discussion on perception of colour and colour measurement.

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Nature of light

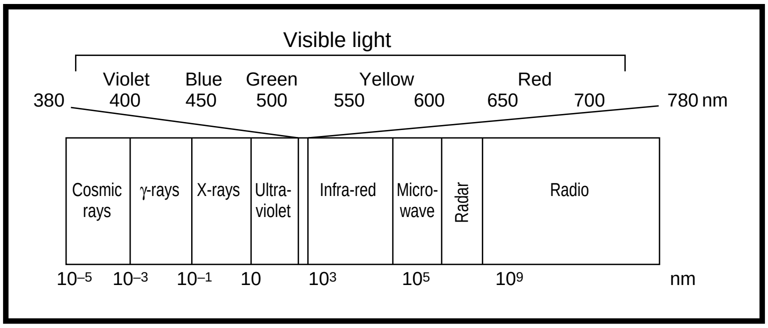

Figure 7.3 *The electromagnetic spectrum*

A clear definition of the nature of white light has proved very elusive, but it is known that light is a form of electromagnetic radiation and that visible light is only a small section of a much broader band of electromagnetic radiation travelling as a wave motion. The electromagnetic spectrum covers wavelengths from 10^{-5} nm[1] (cosmic rays) to wavelengths greater than 10^{9} nm (radio waves). Within this spectrum the only visible radiation is that within the wavelength range between 380 nm (ultraviolet) and 780 nm (red), each wavelength representing a different hue (Figure 7.3).

Colour perception

Various theories of colour vision have been proposed, none of which describes all the observed effects, but their development is a fascinating subject [3]. Here we will look only at modern theories of colour perception on which instrumental measurements are now based.

Trichromatic theory

The combined ideas of Thomas Young and Hermann von Helmholtz are expressed in the hypothesis that the human eye contains three different types of photoreceptor. This proposition received practical support some years later from James Clerk Maxwell. He demonstrated how to match various colours by mixing just three ‘primary colours’ presented as coloured sectors on a rapidly rotating disc. This long-standing theory is referred to as the Young–Helmholtz trichromatic theory of colour vision, but it is only in more recent times that physiological evidence has become available to support the theory. This evidence is an unambiguous distinction between red-, green- and blue-sensitive receptors (cone cells) in the retina, the sensitivity of which is indicated in Figure 7.4.

[1] The wavelength of an electromagnetic wave is measured in nanometres (nm); 1 nm = 10^{-9} m, i.e. 1/1 000 000 000th (one billionth part) of a metre.

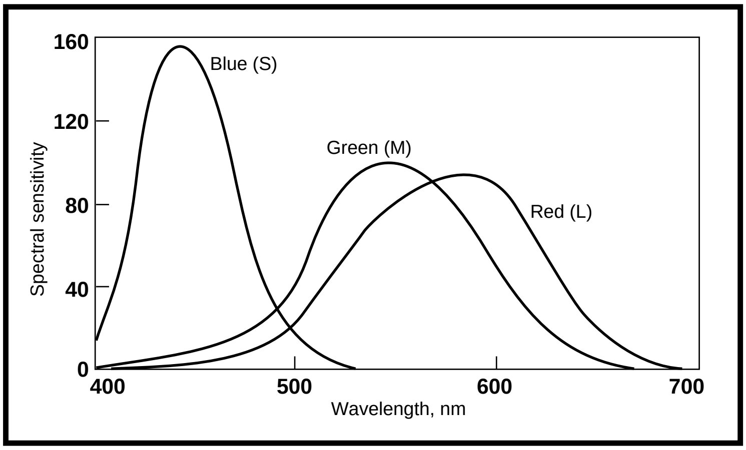

Figure 7.4 *Cone sensitivity curves. S, short wavelength; M, medium wavelength; L, long wavelength*

The other essential contribution was that of Sir Isaac Newton, who demonstrated that white light is dispersed into a spectrum of rainbow colours when passed through a glass prism, and is recombined unchanged when passed through a second prism. To this he added the philosophy mentioned previously that light itself is not coloured, but that light of each individual wavelength is responsible for creating a characteristic sensation of 'colour' within the human brain. Nevertheless, the established convention is that perceived colours are a property of the object with which they are associated, rather than a physiological sensation originating in the retina, and this convention will be adopted here to avoid confusion.

Table 7.1 Relationship between wavelength of absorbed light and hue

Absorbed wavelength (nm)	Hue of absorbed light	Perceived hue
400–440	Violet	Greenish-yellow
440–480	Blue	Yellow
480–510	Blue-green	Orange
510–540	Green	Red
540–570	Yellow-green	Purple
570–580	Yellow	Blue
580–610	Orange	Greenish-blue
610–700	Red	Blue-green

The perception of different hues is a consequence of the absorption of electromagnetic radiation of wavelength between 380 and 770 nm by an object. If the coloured object is transparent (or a solution) the incident light after the selective absorption is transmitted through it. If it is opaque then the residual light is reflected back from the surface.

The perceived colour of the object is determined by the wavelength(s) of the absorbed light. The extent of absorption at a given wavelength is known as the *absorbance*. Light of the remaining wavelengths is transmitted, perceived by the eye and interpreted by the brain as colour. The principle is illustrated in Table 7.1, which summarises the hues produced by the selective absorption of particular wavelengths.

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Table 7.1 accounts for a wavelength range of about 400 nm in the visible spectrum but, as mentioned earlier, the final appearance of the colour is also dependent upon the brightness and the degree of saturation. The three important stimuli may be quantified as the dominant wavelength, spectral purity and luminance.

The *dominant wavelength* of a shade is the wavelength of the spectral colour that needs to be diluted with different amounts of white light to produce variations of shade from the spectral colour through pale shades and finally to white. The *luminance* is defined as 'the luminous flux emitted per unit solid angle or per unit projected area of a real or imaginary surface' [1]. For a coloured object luminance is a measure of the apparent overall reflectance. For a light source it is a measure of the apparent brightness of the light.

The term *spectral purity* refers to the percentage ratio of the luminance of the monochromatic light to the total luminance. Thus the purity would be 100% if the light consisted of only one spectral wavelength – that is, the colour would be saturated.

All three quantities are related, and a change in the value of any one has an effect on the other two. Thus a change in luminance will also affect the hue and saturation. It has been calculated that because of this fact the number of unique hues associated with the visible spectrum is around 7 million for a person with normal colour vision! Obviously, even if it were possible, precise definition of each unique colour by name is impractical. This emphasises the merit of the colour solid as a means of specifying colour, and various efforts have been made to devise a quantitative description of a colour through its location in the colour solid.

Measurement of colour in terms of continuously variable scales is now carried out using colour-measuring instruments. These work on the principle that the sensation of all colours may be stimulated by adjusting the intensities of light of three primary wavelengths, the essential property of any three primary colours being that they cannot be matched by mixing the remaining two. There are several such triads within the visible spectrum, but for experimental convenience the wavelengths chosen are widely spaced in the spectrum and consist of a long, a medium and a short wavelength.

The sensitivity of the human eye at these three chosen wavelengths is very high and the corresponding sensitivities of the red-, green- and blue-sensitive receptors (cones) in the retina are illustrated in Figure 7.4 [3]. The practical consequence is that any colour perceived by the human eye may be imitated with a mixture of red, green and blue lights of appropriate intensities. This

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concept was used as the basis for the specification of colour in terms of primary colours by the Commission International de l'Éclairage (CIE) in 1931.

The convention used when applying a quantitative description to a particular hue is that the three stimuli in question are signified by the use of a bracketed letter preceded by the same letter without brackets, the latter representing the amount of that stimulus required to match the pattern. Thus C units of colour C are represented by C(C), X units of the primary X as X(X) and so on.

Quantitative representation of the colour is achieved using three *tristimulus values*, designated as X, Y and Z, to represent the amounts of the chosen primaries required to match one energy unit for each wavelength. X, Y and Z are the *imaginary primaries* used in instrumental measurements. Their derivation from the real primaries R, G and B for an equal-energy spectrum is necessary in order to avoid the need to use negative tristimulus values (Figure 7.5). For example, consider a situation in a tristimulus colorimeter where light of a particular wavelength is shining on to half of a white surface and the other half is made to match by adjustment of the amounts of the real primaries. There may be a point at which it is impossible to match the wavelength in question by the three primaries alone, in which case the only way to bring about a match is to add an appropriate amount of one of the primaries to the colour being matched. This is equivalent to saying that in some cases negative tristimulus values are required, and this presents instrumental difficulties. For this reason and because of the variations in perceived colour between individuals, originating from physiological differences, the proposed CIE tristimulus values are manipulated mathematically so that they are always positive in value. The result is the X, Y and Z set of imaginary primaries representing red, green and blue, which are used in defining the colour-matching properties of the hypothetical standard observer. The result is similar to the sensitivities of the cones represented in Figure 7.4.

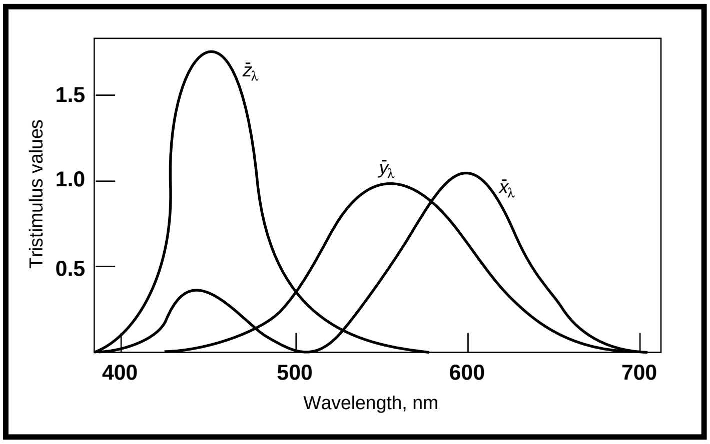

Figure 7.5 *Tristimulus values for each wavelength in a constant-energy spectrum; the results represent those of an average observer with normal colour vision using as primaries [R] 700 nm, [G] 546.1 nm, [B] 435.8 nm*

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Additive colour mixing

In additive colour mixing all colours can be matched by using appropriate amounts of primary colours corresponding to X, Y and Z. Thus for *C* units of colour C, we can write Equation 7.1:

$$C(\mathrm{C}) = X(\mathrm{X}) + Y(\mathrm{Y}) + Z(\mathrm{Z}) \tag{7.1}$$

where the symbols have the significance previously defined.

The scales for X (the red stimulus), Y (the green stimulus) and Z (the blue stimulus) are adjusted so that the quantities of each component required for white light are equal. Thus 1 part X + 1 part Y + 1 part Z = white.

If we therefore direct equal amounts of red, green and blue light on to a white surface it remains white, but if the intensity of any of the three is varied the sensation of colour is produced. Thus if only red and green lights are used a yellow sensation is produced; green and blue produce cyan; red and blue produce magenta (Plate 7). This is the principle of *additive mixing*.

Subtractive colour mixing

Obviously, the appearance of dyed fabric in daylight is not contrived by illuminating the fabric using primary coloured lights of appropriate intensity. The sensation of colour in this case occurs because the dyes absorb some of the wavelengths of the incident white light. That is, the light reflected back to the observer is no longer white, and the fabric is perceived as being coloured. In this case the origin of the colour arises from a subtractive process. The principle of *subtractive colour mixing* is illustrated in Plate 8.

In subtractive mixing the primary colours used are magenta, yellow and cyan. Comparison of Plate 8 with Plate 7 shows that cyan may be obtained additively by mixing the green and blue primaries, yellow by mixing the red and green primaries, and magenta by mixing the red and blue primaries. Thus each additive primary is representing one of the three components of white light. The subtractive primaries are different because they represent a mixture of two of the additive primaries, i.e. one of the three components of white light is absorbed whilst the two remaining are reflected (or transmitted through a solution). For this reason the subtractive primaries are often designated as negative primaries:

magenta = – green (1 part red + 1 part blue transmitted/reflected)

yellow = – blue (1 part red + 1 part green transmitted/reflected)

cyan = – red (1 part blue + 1 part green transmitted/reflected).

This nomenclature has the advantage of indicating which of the three additive primaries has been absorbed.

In subtractive mixing, therefore, the colour perceived is determined by what has been removed from the incident white light. Thus if the cyan (– red, i.e. blue + green remaining) and magenta (– green, i.e. red + blue remaining) are superimposed, only the blue component remains unabsorbed and the perceived colour is blue. Similar reasoning shows that superimposition of magenta and yellow results in the transmission only of the red component of white light, and the superimposition of cyan and yellow only of the green (Plate 8).

The functioning of the human eye and of colour-measuring instruments, however, are both based on the use of additive primaries irrespective of the process by which the colour is produced. The spectrophotometers used for colour measurement are designed to enable a coloured pattern and a standard white surface to be illuminated under conditions that conform with carefully considered geometrical requirements, using a standardised source of illumination. Reflectance measurements for both the pattern and the white standard are made over appropriate intervals of the visible spectrum. The information from the sensors is transmitted to a microprocessor where the results are converted into X, Y and Z values for display on a monitor.

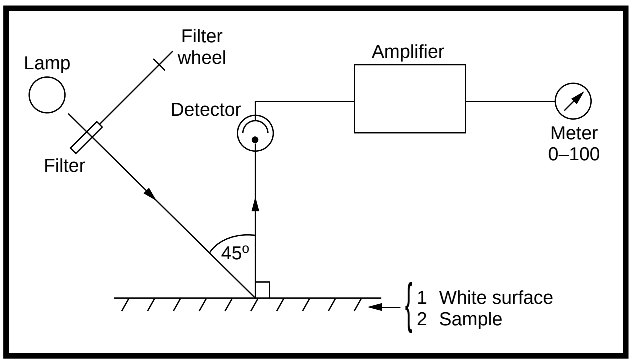

Figure 7.6 *Basic trichromatic colorimeter*

Alternatively a tristimulus colorimeter may be used. This also enables reflectance measurements to be made of the coloured pattern alongside a white standard, but in this case appropriate red, green and blue filters are inserted successively between the collimated beam of the standard source of illumination and the surface in question (Figure 7.6). The instrument is readjusted as each filter is placed into the beam. The

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reflectance of the white surface represents 100% reflectance. The lower reflectance of the coloured sample is then measured and compared with the result for the white surface. The reflectance values are transmitted to a microprocessor and displayed as the tristimulus values.

For opaque coloured objects the relationship between the spectral power of the standard illuminant at wavelength λ (E_λ) and the spectral reflectance characteristic of the coloured object (R_λ) are related to the tristimulus values as shown (Equation 7.2):

$$X = \Sigma E_\lambda \bar{x}_\lambda R_\lambda$$

$$Y = \Sigma E_\lambda \bar{y}_\lambda R_\lambda$$

$$Z = \Sigma E_\lambda \bar{z}_\lambda R_\lambda \qquad (7.2)$$

where $\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$, the spectral response characteristics of the standard observer, represent the number of units of X, Y and Z required to match one unit of energy of wavelength λ. The sigma (Σ) sign indicates that the appropriate values for each increment of wavelength, between 380 and 760 nm, are added together to obtain the final value. The X, Y and Z tristimulus values therefore indicate the relative quantities of light of the red, green and blue regions of the spectrum reflected from the surface, as perceived by the eye.

On this basis a perfectly white surface viewed under an equal-energy light source would be represented by the expression $X = Y = Z = 100$, and a black surface by $X = Y = Z = 0$. The situation with a real light source differs from this ideal situation, however, and in reality X and Z do not equal 100.

In all accurate colour matching, consistency in both the quality of the incident light and the conditions of viewing is of particular importance. The energy distributions in the spectra of different sources are, in practice, different. Consequently the energy distribution of light reflected back from the pattern from each source will have its own distinct profile, and both the visual appearance and tristimulus values will be affected. The quality of various illuminants has therefore been extensively studied; those with defined spectral energy distribution are now specified by the CIE. The source designated as illuminant A represents the light from a tungsten filament lamp. Those designated as illuminant B and illuminant C correspond to direct sunlight and average daylight respectively. An improved series of sources, the D illuminants, are based on a mixture of both sun and skylight and their use is now becoming more widespread.

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Chromaticity diagrams

The concept of a colour space has proved to be invaluable in colour measurement. Although a three-dimensional representation is inconvenient, the practical solution has been to convert the tristimulus values into fractional quantities referred to as *chromaticity coordinates*, as shown in Equation 7.3:

$$
\begin{aligned}
x &= X/(X+Y+Z)\\
y &= Y/(X+Y+Z)\\
z &= Z/(X+Y+Z)
\end{aligned}
\qquad (7.3)
$$

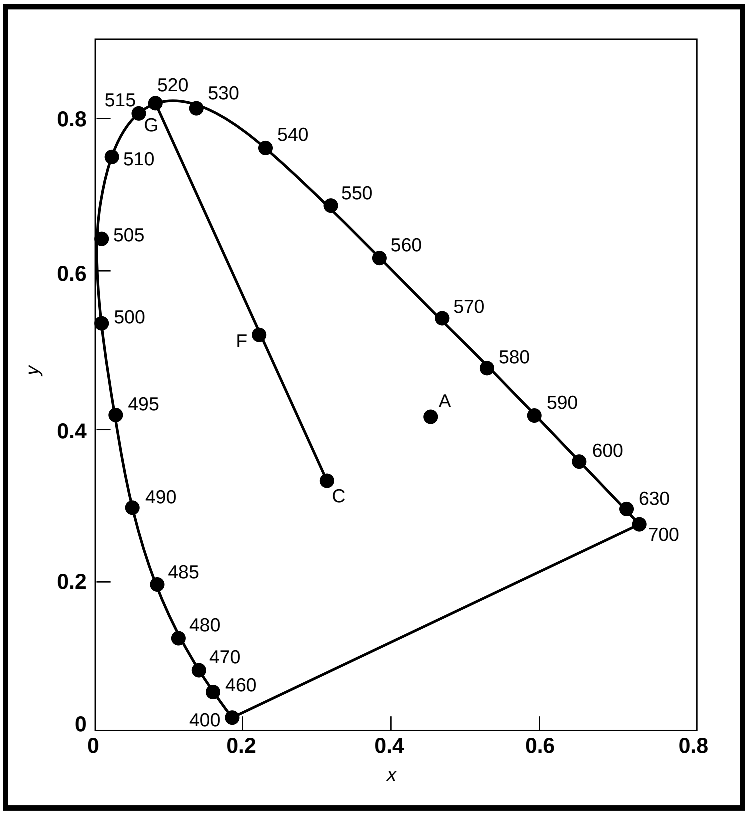

Figure 7.7 *Chromaticity diagram*

It therefore follows that $x + y + z = 1$ for all colours. Thus only two chromaticity coordinates, x and y, need to be defined; since $x + y + z = 1$, z can always be found by a simple calculation ($z = 1 - (x + y)$). Values of x and y can be plotted on a two-dimensional graph, and X and Z can also be calculated from x, y and Y, the latter three parameters being used to specify any colour on a two-dimensional plot. A colourist regards this as a statement of the *quality* of the colour. (The use of the term 'quality' in this context should not be confused with the broader statements concerning factors such as fastness and levelling properties, discussed in previous chapters.)

A plot of x against y is called a *chromaticity diagram*. The line joining the spectrum of colours plotted as values of x and y obtained from the tristimulus values of the standard observer is

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called the *spectrum locus*. The position of each wavelength on the spectrum locus is shown in Figure 7.7.

The effect of illuminant source on appearance is also emphasised in Figure 7.7, since point A and point C represent the appropriate values for the same neutral pattern under illuminant A and C respectively. A further property of the chromaticity diagram is that if white light from illuminant C is mixed with monochromatic light of wavelength, say, 520 nm (green), all the possible greens will fall on a line CG; they will appear as various shades of green, ranging from white through pale green to the saturated hue at the spectrum locus. The same principle holds good for any other wavelength on the diagram. A defect of this system is that equal changes in the numerical quantities do not produce equal differences in the perceived colour.

Various attempts have been made to improve the visual uniformity of the colour space, and in 1970 the Society of Dyers and Colourists, and later the ISO, recommended a colour space that provided the precision necessary for specifying colour-difference measurements for coloured textiles. At the present time tristimulus values X, Y and Z, for a particular combination of illuminant and observer, are transformed into alternative units in relation to the corresponding values for a sample reflecting 100% of the light at all wavelengths (denoted X_o, Y_o and Z_o) in the CIE system. The new so-called *CIELAB coordinates* are represented by Equation 7.4:

$$\begin{aligned} L^* &= 116(Y/Y_o)^{1/3} - 16 \\ a^* &= 500[(X/X_o)^{1/3} - (Y/Y_o)]^{1/3} \\ b^* &= 200[(Y/Y_o)^{1/3} - (Z/Z_o)]^{1/3} \end{aligned} \tag{7.4}$$

where the asterisk signifies that CIE-defined units have been used. This covers all colours except those with very low tristimulus values.

The relationship between the coordinates in the colour space is shown in Figure 7.8. In this more uniform system a^* and b^* are plotted instead of x and y, and a representation of the colour map that this produces is shown in Plate 9.

A further customer aid has been provided as part of the ICI colour atlas (page 142) in the form of a grid that can be placed over a CIE colour map. The grid consists of a card of the same dimensions of the colour map into which are cut viewing holes coinciding with the coordinates of the appropriate dyes on the colour atlas. Lines are drawn between adjacent dyes to indicate the various hues that may be obtained by mixing the dyes in different proportions. With three dyes the

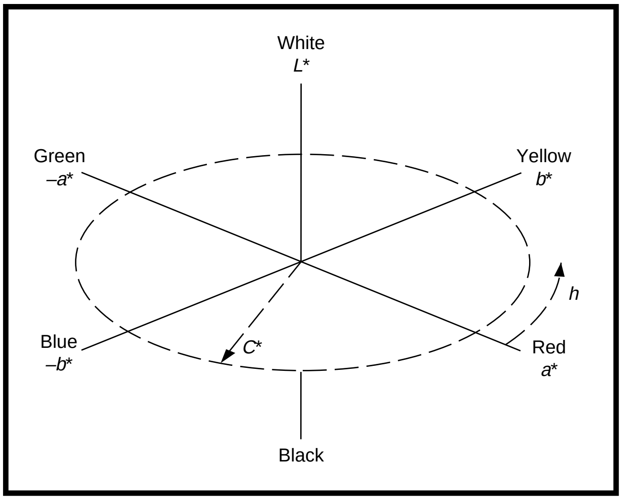

Figure 7.8 *CIELAB colour space*

triangular area contained by the three lines drawn on the colour map represents the range of colours or the 'colour gamut' that can be obtained by mixing these dyes in different proportions. An example of the position of vat dyes on the colour map is given in Figure 7.9.

Colour differences

The colour coordinates now developed are sufficiently accurate to be used to quantify the colour differences between two patterns. This entails using the sets of the L^*, a^* and b^* values and substitution in the colour-difference equation (Equation 7.5):

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \qquad (7.5)$$

where ΔL^*, Δa^* and Δb^* represent the differences between the corresponding units of each sample.

Table 7.2 Grey scale ratings represented as colour differences in CIELAB units

Grey scale rating	Effect (ΔE)	Stain (ΔE)
5	0	0
4	1.7	4.3
3	3.4	8.5
2	6.8	6.9
1	13.6	34.1

In this way the grey scales described on page 8 for assessing the visual effect of a treatment on a coloured pattern may be quantified; these are given in CIELAB units in Table 7.2.

In industry there is usually greater tolerance towards depth and/or brightness variation than towards hue variation. Consequently further equations have been developed that take into account differences in lightness and in chroma, one of which, the CMC equation, has been issued as a draft British Standard. The subject of colour difference is very complex, however, and readers requiring more detailed information are advised to consult a more advanced treatise [3,4].

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Colour constancy and metamerism

At one time or another, nearly everyone has carefully chosen and purchased a coloured article from a store only to find that in another location the colour was not exactly what had been expected. The disappointment may have been due either to poor colour constancy or to metamerism. Both phenomena are related to a change in the spectral energy distribution of the light reflected back to the eye from the article in question in moving from one light source to another.

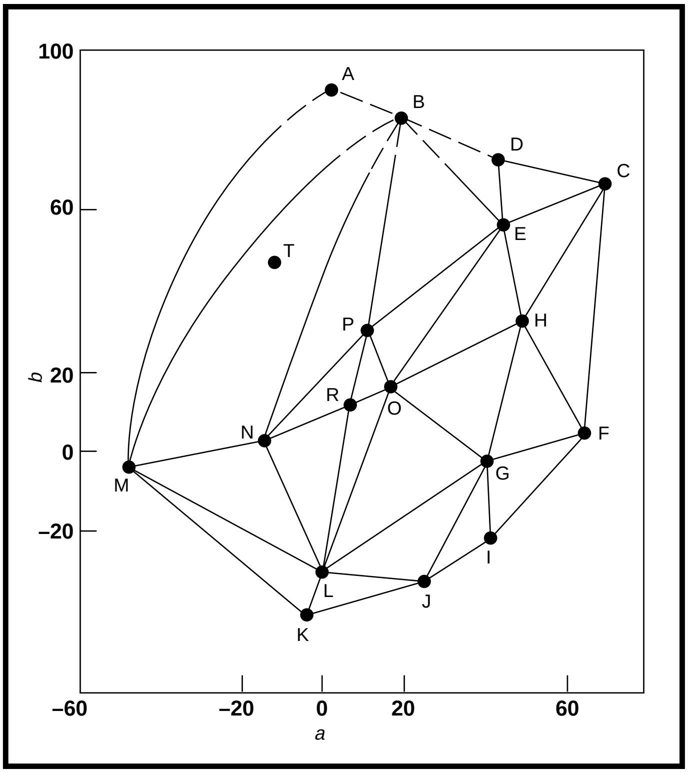

Figure 7.9 *Dye map for vat dyes on mercerised cotton (L planes 48–74)*

A	*CI Vat Yellow 2*	*J*	*CI Vat Violet 21*
B	*CI Vat Yellow 12*	*K*	*CI Vat Blue 6*
C	*CI Vat Orange 7*	*L*	*CI Vat Blue 64*
D	*CI Vat Orange 15*	*M*	*CI Vat Green 1*
E	*CI Vat Orange 17*	*N*	*CI Vat Green 30*
F	*CI Vat Red 1*	*O*	*CI Vat Brown 1*
G	*CI Vat Red 13*	*P*	*CI Vat Brown 30*
H	*CI Vat Red 14*	*R*	*CI Vat Brown 49*
I	*CI Vat Violet 3*		

Colour constancy refers to the extent to which the appearance of an individual coloured article remains the same when viewed under different light sources, irrespective of the dyes used. *Metamerism*, on the other hand, refers to a change in the appearance of two patterns dyed with different dyes that have been matched under one light source, when they are viewed under a different source. It may be that the two patterns are no longer a match because, although they have identical visual appearances and tristimulus values under a specified illuminant, their reflectance curves are very different.

Both the perceived colour and the corresponding tristimulus values derived from the hypothetical standard observer are a function of a balance between the spectral qualities of the illuminant source and the wavelengths absorbed by the coloured object. Thus, if some wavelengths critical to the appearance of the colour viewed under one illuminant are missing in a second, they will not be present in the light reflected back to the observer. The reflectance spectrum of the

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pattern will then be deficient in these wavelengths and therefore the visual appearance of the colour will change in moving from one illuminant to another.

Although this *illuminant metamerism* is the most frequent in occurrence, other sources of discrepancy can arise from the slight differences that can exist in the colour vision of different observers (*observer metamerism*). Differences in appearance may also be a function of the angle of view (*geometric metamerism*) or of the changes in the area being viewed (*field size metamerism*). These are additional problems for the dyer who is formulating a recipe to provide the required match. They are also taken into consideration in matching through instrumental methods based on the CIE description of the position of a colour in colour space.

Colour match prediction

The significant success in the use of computer-aided colour matching is reflected by the confidence of the increasing number of dyers who plan to achieve 'first time' matches of the target shade. The systems used measure the reflectance of a pattern, convert the results into tristimulus values and synthesise a matched reflectance curve from stored reflectance data for the available dyes. As well as being influenced by the absorption properties of the dyes, the appearance of a woven fabric is also governed by the scatter of light from its surface. This in turn is controlled by other factors such as weave pattern, the fineness of the individual threads and their orientation with respect to the illuminating source.

The Kubelka–Munk equation

All these properties are embodied in the Kubelka–Munk analysis of the reflectance of a surface. The appropriate form of the equation for textile surfaces is given in Equation 7.6:

$$K/S = (1 - R)^2/2R \qquad (7.6)$$

where R is the reflectance of an infinitely thick layer of material illuminated with light of a known wavelength, K is the absorption coefficient and S is the scattering coefficient. The function K/S is directly proportional to the concentration of colorant in the substrate.

One of the properties of this relationship is that for a mixture of dyes the total value K/S may be calculated for any wavelength by summing the appropriate values for each dye. Thus for dyes of

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concentration c_1, c_2, and c_3, having absorption coefficients K_1, K_2 and K_3 respectively, the total K/S value is defined by Equation 7.7:

$$K/S = c_1(K_1/S_1) + c_2(K_2/S_2) + c_3(K_3/S_3) + K_s/S_s \qquad (7.7)$$

where the subscript s refers to the substrate.

The absorption characteristics for a range of dyes on a specified substrate over a range of visible wavelengths are measured. These data are stored in the computer memory for later use in calculating the proportion of each dye required to match the reflectance values of the pattern. Of course the ideal would be for the information to be made available for all wavelengths, but in fact the practical requirements may be adequately met by the use of 16 wavelengths spaced at 20 nm intervals throughout the visible spectrum.

Practical use of instrumental colour measurements

The X, Y and Z values of the shade required are used in the recipe prediction for matching shades. They can be fed into the computer together with reflectance information about the substrate. The stored absorption coefficients for the relevant dyes are called into play and the computer calculates the expected reflectance for each of the 16 wavelengths at given starting concentrations for the dyes used in the mixture. The result is converted into predicted X, Y and Z values; these are compared with the target values and the differences assessed. If the differences are too large, the program permits adjustment of the dye concentration for a further calculation. The process continues until the predicted X, Y and Z values are sufficiently close to the target values, at which stage the recipe is printed out.

Recipe correction

Although the ultimate aim is to provide a prediction that is 'right first time', it would be optimistic to expect any system to operate with consistent perfection. Colour matching is not an exact science, and there are many deviations from the theoretical concepts upon which instrumental colour matching are based. The systems used are in a perpetual state of development and refinement. Often unexpected variables may arise for which no account has been taken in the design of the operating

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program. It is easy to recognise contributory human errors in activities such as setting the operating parameters of the equipment or weighing the colour. These frequently have an easily identifiable cause, but the origin of other deviations can be more subtle and can call for careful refinement of operating procedures. For example, correction may be needed when the physical structure of the substrate is not identical to that used in the preliminary calculation. Furthermore, when applied at the calibration stage the dyes may behave differently from when they are applied in admixture, because of interaction with other dyes in the formulated recipe. Factors like these can give rise to differences between the actual and the computed results. Such differences may also occur when successful small-scale trials are scaled-up to full production, simply because of mechanical factors involved in dealing with a large bulk of material that cannot be foreseen from a small-scale trial.

Correcting bulk-scale dyeing is therefore another area in which computerised colour manipulation is of value. Instrumental measurements are able to provide values for the differences between the *X*, *Y* and *Z* values of the dyed and target patterns; these are then used to calculate a recipe suitable for making good the deficit.

Other applications

The information available within a commercial colour-matching system is not confined to the production of the final shade. It also enables the most economical route to the target to be established through sorting procedures, and similar principles are involved in predicting the likely degree of metamerism and colour constancy. Other relevant technical information may be stored for use in aiding the preliminary dye selection. Thus fastness properties, stability of the dye recipe, level-dyeing characteristics and the effect of pH and electrolyte may all be catalogued for easy reference and use at the appropriate stage of the operation. Relevant statistical information is also updated automatically, thus aiding inventory control and other management functions

Monitoring the quality of the colour of dyed fabric is a critical matter in clothing factories. It is not unusual for the dyed fabric to arrive from different sources, and even slight variations will become more obvious if they appear on adjacent panels of the assembled garment. Difficulties of this kind are therefore circumvented by grouping dye lots into closely matching batches through the application of colour-difference formulae. This is another area where the subjective nature of conventional visual inspection is being replaced. Colour-difference measurements have also become

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a valuable tool in pass/fail systems in which coloured articles are compared instrumentally against prescribed colour tolerances.

Whiteness and yellowness

Whiteness suggests cleanliness and freedom from contamination and as such it is taken as an indicator of quality. Nevertheless, objective measurement and meaningful numerical expression of the condition has proved technically complex. The CIE expression for a *whiteness index* has been available, in the form of Equation 7.8, only since 1982. It represents whiteness in terms of colorimetric values for the specimen and the chromaticity coordinates of the illuminant:

$$W = Y + 800(x_n - x) = 1700(y_n - y) \qquad (7.8)$$

where x, y and Y are the colorimetric values for the specimen under a specified form of illuminant D, and x_n and y_n are the chromaticity coordinates of the light source. A value for W of 100 represents a perfect reflecting diffuser.

Treatment with fluorescent brightening agents can lead to reflectance values of up to 150. Although the pattern appears to become whiter, the change in appearance is due to a change in chroma towards blue, and this fact is expressed in quantitative form as the 'tint factor'.

Allied to the appearance of the uncoloured fabric is the yellowness, which suggests scorching, or degradation by light or by gases. Various scales for yellowness have been devised in an attempt to establish a yardstick by which undyed fabric can be assessed for quality.

Clearly, colour measurement is becoming of even greater importance in defining the quality of the appearance of textiles. Computer-aided dye selection is just one area in which modern methods are aiding the rapid response of the manufacturer to the demands of the market.

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