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Chapter 9: Modelling colour properties for textiles

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1. Introduction

Colour exists in more than 1 million visually distinct shades, and it subtly influences your understanding of the environment, your mood and your purchasing decisions. Colour is therefore studied, created, and manipulated as a means of creative expression, and for obtaining commercial advantage in the design and production of goods or services. Artists may take a lifetime to master the subtleties of expressing their ideas in colour, and the resulting creative style may then be immediately recognizable as a visually distinct and uniquely expressed message. By contrast, internationally standardized colorimetric simulation and modelling systems are used for the technical specification of colour (Berns 2000a).

1.1 The key factors and principles in modelling colour

Modelling is needed because colour exists only as a subjective visual sensation that is induced by light of varying wavelength. It follows that colour has no objective physically measurable existence, and the only way it can be reliably specified is to create ‘psychophysical’ models of the sensation that are quantified by measuring the power of the electromagnetic light stimuli that cause it.

In order to discriminate between the distinct hues of the visible spectrum at least twelve parameters are required, and in practice thirty or more are often used. A light stimulus must therefore be specified using an *N*-dimensional ‘Spectral Power Distribution’ or SPD. An SPD quantifies the amount of power present in each subdivision of the spectrum and is often referred to as a ‘spectral curve’.

Unlike its physical cause, the colour sensation has just three dimensions because the eye senses colour using three types of receptor cell with differing sensitivities to light at each wavelength. It follows that the receptor response can be represented numerically using only three descriptive parameters. This many-to-one relationship between the physical stimulus and the psychophysical response must be reflected in the modelling process, which in consequence has two key objectives:-

1) To establish a system that uses a unique triplet of numeric ‘colour identity co-ordinates’ to specify each of the one million plus possible sensations of colour. Think if you will in terms of establishing a three dimensional ‘colour space’ where the colours are located by their **hue** (blue, green red etc), **purity** (neutral, dull, bright, vibrant), and **lightness** (light, pale, dark, full).

2) To represent the effects of additive colour mixture using a mapping by vector sum onto points in this colour space. The intent is to establish a spectrally defined model that is capable of predicting colour matches correctly, including those between physically different stimuli.

1.2 Conditional or metameric colour matches

Visual matches between physically identical stimuli are termed ‘invariant’, but a much larger set of physically different stimuli are also ‘conditional’ or ‘metameric’ matches to any given stimulus. Such matches are only evident in a restricted range of viewing contexts, but both types of visually matching physical stimuli can in practice be identified using a vector sum model that takes the viewing context into account as in Figure 9.1.

Insert Fig 9.1 (see page 26) near here

The correctness of predictions by the vector sum mapping in Fig 9.1, is critically dependent on three factors. (a) The scaling must be precisely equated over all dimensions in which addition may occur (these are denoted in Figure 9.1 by λ). (b) The numeric scaling must be strictly constant within each dimension, and (c) The ratios of proportionate value relative to the defined scaling, must be a constant property of all possible added components.

These factors are all successfully realized in the CIE Colorimetric model, which is described in more detail in Section 2. In the CIE system, the prerequisite constancy of scaling is achieved by calculating the predictive sum in terms of the units of physical stimulus cause, and within the CIE model the numeric stimulus values are also normalized at the axis of visual neutrality in order to equate the psychophysical scaling inter dimensionally. The scaling thus established is then re-weighted over each of the Long, Medium and Short wavelength (L, M and S) receptor-channel responses using constant proportionation ratios. Thus at a given wavelength, the response might be subdivided over the L, M and S channels in the proportions of say 0.49: 0.31: 0.20, or perhaps 0.18:0.81: 0.01.

1.3 Finding the linear model

Demonstrating that a descriptive vector sum makes accurate predictions clearly adds confidence in the model. It is however both possible and potentially important to quantify the statistical confidence level of those predictions, and it is also possible to validate any vector sum formally by reference to its axiomatic definition (see (Oulton 2009) for more details). Historically, the use of axiomatically defined vector systems was developed in the physical domain, (that is to say in the real world). The resultant vector systems are then intrinsically linear, and the numeric scales, unit values, and axes of spatial orientation are fundamental physical constants of Newtonian physics (Halmos 1974).

Linear vector systems can also be used to model nonlinear phenomena if one or more linearization steps are used to map the observed data values onto the descriptive spatial model. This process is described as ‘finding the linear model’ in an important paper entitled ‘A generic approach to color modeling’ by Roy S. Berns (Berns 1997).

When establishing the linear model, it is advantageous (Oulton 2009) to distinguish between the intra-dimensional scaling of the model, and the essentially multi-dimensional vector additive effects.

Insert Fig 9.2: Near here

In Fig 9.2, the preliminary linearization and normalization step ‘a’ establishes a model with scales that are fully defined and uniformly equivalent within each dimension of cause and effect. The constant and linearly cross-dependent definition of additive value ‘b’ thus enabled then becomes a distinct and separately quantifiable component within the overall relationship being modelled.

1.4 Summary

- The literature on colour arises from the disciplines of vision science, colour science, and practical colorimetry, and it covers many topics that are relevant to the modelling of textile colour and texture. Colour imaging and colour reproduction in such fields as computer systems, photography, television, video and the internet also have a comprehensive literature.

- The sensation of colour is the response of the human visual system to light stimuli, whose power content as a function of wavelength is specified by a spectral curve or SPD (spectral power distribution).

- Each visually distinct band of the spectrum generates a uniquely hued colour sensation. It is therefore necessary to divide the spectrum into many such bands in order to describe the colour-causing electromagnetic stimuli unambiguously.

- The visual response can be modelled using a three dimensional vector sum over wavelength, because the eye discriminates colour using three distinct short, medium and long wavelength responses.

- In virtually all instances of colour modelling it is advantageous to establish a linear vector sum representation of the phenomenon being modelled, and it is often necessary to include a dataset linearization step when ‘finding the linear model’ (Berns 1997).

2. The types of model used

The disparate list of possible colour model types includes the standardized CIE colorimetric models, colour calibration models, and models that enable colour communication and colour networking systems. It further includes the models used in photographic video and computer generated colour systems; colour appearance models, and descriptive colour order systems such as colour atlases.

2.1 The CIE Standard Observer, Standard Illuminant and colour co-ordinate models

The letters CIE stand for the Commission Internationale de L'Eclairage (or in English the International Commission on Illumination) which is the main international standardization agency for colour (CIE 2008). The key CIE models include the 1931 and 1964 CIE Standard Observer models, a comprehensive set of Standard Illuminant definitions, and the CIELAB model for colour difference (CIE 2008, publication 15.2004 etc). These models are used to quantify colour identity in CIE XYZ colour space and to predict metameric colour matches by the vector sum transformation of physical SPD measurements.

In the CIE system for surface colours, the physical definition of any given colour is a spectral curve that specifies the amount of light reflected at particular wavelength intervals across the visible spectrum. Fully identifiable and traceable CIE Standard Observer and Standard Illuminant data sets (see Berns 2000b), are then used in combination with these reflectance values to weight the vector sum colour definition.

Insert Fig 9.3: The three defining factors of the object-colour sensation.

Note that all three of the defining factors in Figure 9.3 have a detailed spectral, that is to say multi element definition within the tristimulus vector sum. A given pair of surface reflectance curves may therefore be a conditional visual match that fails under some light sources, thus exhibiting ‘illuminant metamerism’. A pair of surface colours that match when viewed in daylight, can thus become a significant mismatch when viewed in artificial light of one sort or another. They may alternatively be a mismatch according to some imaging device or human observer, thereby exhibiting ‘observer metamerism’.

An internationally agreed set of equations (CIE 2008, ASTM 2008) quantify the observed colour using the three CIE colour co-ordinates *X, Y, Z* as follows:-

$$
\begin{aligned}
X &= k.\int_{830nm}^{360nm} R_\lambda.S_\lambda.\bar{x}_\lambda.d_\lambda \\
Y &= k.\int_{830nm}^{360nm} R_\lambda.S_\lambda\bar{y}_\lambda.d_\lambda \\
Z &= k.\int_{830nm}^{360nm} R_\lambda.S_\lambda.\bar{z}_\lambda.d_\lambda
\end{aligned}
\qquad (1)
$$

Where with reference to the perfect reflecting diffuser:

R_λ is the reflectance factor (on a scale from zero, to one).

S_λ is the relative spectral power of a CIE standard illuminant, and

$\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$ is a set of CIE standard observer colour matching functions or CMFs.

The normalizing factor *k* is given by $k = 100/\left(\int_{830nm}^{360nm} R_\lambda.S_\lambda\bar{y}_\lambda.d_\lambda\right)$ for the perfect reflecting diffuser.

(2)

In standard CIE practice (CIE 2008) the integrals of both equations (1) and (2) are approximated by summation over a set of *N* fixed-interval sub-divisions of the visible spectrum:-

$$
\begin{aligned}
X &= k.\sum_\lambda R_\lambda.S_\lambda.\bar{x}_\lambda.d_\lambda \\
Y &= k.\sum_\lambda R_\lambda.S_\lambda\bar{y}_\lambda.d_\lambda \\
Z &= k.\sum_\lambda R_\lambda.S_\lambda.\bar{z}_\lambda.d_\lambda
\end{aligned}
\qquad (3)
$$

Where: Each element of the summation (denoted by λ) is quantified as a sub-band of the visible spectrum $\lambda = 1$ *to N*, and standard CMF and Standard illuminant tables are published for a standardized set of bandwidths and spectral range definitions (ASTM 2008).

The constant *k* again normalizes the calculation to $Y = 100$ for the perfect reflecting diffuser with $R_\lambda = 1$ at all wavelengths

The resulting CIE co-ordinates *X, Y, Z* specify colour identity and predict sets of metamerically equivalent visual sensations. Note however that in the spatial arrangement of point identities thus established the scaling of visual difference is specified in terms of watts of stimulus power, not units of visible difference.

Observed visual differences in colour are found to exhibit a nonlinear scaling relative to *X, Y, Z* tristimulus values, and the scaling is also both wavelength and stimulus intensity dependent. Visual colour difference as distinct from colour identity is therefore represented in the standard CIE L*a*b* model using the following equations (Berns 2000), where the relevant *XYZ* values are mapped by nonlinear projection and axis transformation onto equivalent CIELAB values:-

$$L^* = 116.(Y/Y_n)^{1/3} - 16$$
$$a^* = 500.\left[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\right]$$
$$b^* = 200.\left[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\right] \quad (4)$$

Where: X_n , Y_n and Z_n are the tristimulus values for the reference white, and X/X_n, Y/Y_n , $Z/Z_n > 0.008856$.

L^* defines incremental steps of visual lightness,

a^* denotes a dimension of redness/greenness, and

b^* denotes a dimension of yellowness/blueness.

The perhaps more intuitive cylindrical / polar co-ordinates of colour, Lightness, Chroma and Hue are then quantified as follows where Chroma is a radial distance from the neutral axis: The essentially circular Hue parameter loops back from blue to red via purple to complete the Hue circle, and Hue becomes an angular measure:-

Chroma $C^*_{ab} = \left(a^{*2} + b^{*2}\right)^{1/2}$ (5)

Hue angle $h_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right) = \arctan\left(\frac{b^*}{a^*}\right)$ (6)

When either X/X_n or Y/Y_n or Z/Z_n is *less* than 0.008856, the relevant cube root functions in equation (4) must be replaced by a linear re-weighting. A re-scaling constant 7.787 that is common to all three dimensions is used, and the other three re-scaling constants, 116, 500, and 200 (respectively for L^* a^* and b^*) are retained unaltered. Thus, the value $(Y/Y_n)^{1/3}$ is replaced by $7.787(Y/Y_n)$ etc.

The reverse projection from L^* a^* and b^* onto X, Y, Z for X/X_n, Y/Y_n , $Z/Z_n > 0.008856$ is given by:-

$$X = X_n\left(\frac{L^*+16}{116} + \frac{a^*}{500}\right)^3$$
$$Y = Y_n\left(\frac{L^*+16}{116}\right)^3 \quad (7)$$
$$Z = Z_n\left(\frac{L^*+16}{116} + \frac{b^*}{200}\right)^3$$

Chroma C^*_{ab} and Hue angle h_{ab} values can also be projected back onto a^*, b^* values as follows:-

$$a^* = C^*_{ab} Cos(h_{ab}) \qquad (8)$$

$$b^* = C^*_{ab} Sin(h_{ab}) \qquad (9)$$

Under the L* a* and b* co-ordinates quantified by equations (4) to (9) the component lightness and chromatic differences are respectively designated as ΔL, Δ a* and Δ b*, and the Pythagorean or RMS sum distance ΔE, between any pair of points in colour space is then given by:-

$$\Delta E = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2} \qquad (10)$$

The co-ordinate scaling of CIELAB colour space is used in industry (often with additional modelling extensions) to quantify visual match acceptability and to set production colour tolerance standards.

Many more extensive accounts of the CIE System and its applications have been written; colour scientists tend to be zealous missionaries for their art. The recommended such version is that given by Berns in 'Billmeyer and Saltzman's Principles of Color Technology' (Berns 2000b).

2.2 Colour calibration models

Many task-specific colour calibration models are used in chemical analysis, and dye lab experiments. Such experiments typically use the colour of clear solutions and the absorption of monochromatic light in a discipline called absorptiometry to determine coloured solute concentrations down to the parts per million level (Berns 2000c). The light absorption property of a given solute as a function of wavelength is established by measuring fractional light transmission values for a set of known concentrations. Calibration graphs are then constructed using a well established data linearization step that converts light transmission data into light absorbance values. The fractional light transmittance of a clear coloured glass or dissolved colorant is given by:-

$$T_\lambda = \frac{I_t}{I_o} \qquad (11)$$

Where T_λ denotes the ratio of transmitted light I_t to incident power I_o, for some (typically monochromatic) sub-component of the visible spectrum, and T_λ is a characteristically constant property of the light absorbing substance that is independent of the incident light intensity I_o.

Given an infinite sequence of light absorbing layers each of which has a transmittance of say $T_\lambda = \frac{1}{2}$, it is readily apparent that the overall value of I_t relative to I_o will decrease exponentially as each successive layer absorbs half of the light that passes though it. The dependence of T_λ on the light-path length and colorant concentration is thus given by:-

$$T_\lambda = \frac{I_t}{I_o} = e^{-\varepsilon_\lambda .l.C} \qquad (12)$$

Where: l is the overall length of the light path in cm, C is the colorant concentration in Moles/litre and ε_λ is the wavelength dependent constant known as the molar coefficient of light absorption.

The linear model of additive light absorbance values A_λ is thus given by:-

$$A_\lambda = -\log_e(T_\lambda) = \log_e\left(\frac{1}{T}\right) = \varepsilon_\lambda .l.\ C \qquad (13)$$

Where: For monochromatic incident light of wavelength λ, a path length l, and mixtures of non-interacting colorants of concentration C_1 , C_2 etc,

$A_{\lambda\ tot} = \varepsilon_{\lambda\ 1} .l.\ C_1 + \varepsilon_{\lambda\ 2} .l.\ C_2$ ….etc

2.2.1 Calculating component effects and resolving cross dependency

In the above case involving coloured solutions, a true linear model of simple subtractive colour mixture may be established by the logarithmic linearization in equation (13). The relevant constants $\varepsilon_{\lambda\ 1,2,3}$ are derived from the slopes of calibration graphs of A_λ versus concentration C for single-colorant monochromatic light absorbance. In a three colorant mixture a 3X3 matrix of nine coefficients is required in order to resolve the cross dependency of $A_{\lambda\ tot}$ on the individual concentrations $C_{1,2,3}$. A set of three calibration graphs is therefore derived for each colorant. The individual unknown concentrations of the colorants can then be calculated via optimal sets of simultaneous equations.

Note: It is often assumed that the wavelengths of maximum absorption for the colorants present should be used as the analytical basis. This is however at best a half truth, and the guiding principle must be to base the analysis on a careful inspection of the spectral curve graphs for the colorants that are present in the mixture. The objective is to differentiate their absorption properties as completely as possible. That is to say, the ε_λ values for the colorants in question should follow a ‘hi, lo, lo / lo, hi, lo / lo, lo, hi’ pattern as closely as possible at the chosen wavelengths.

2.2.2 Calibrating digital colour reproduction systems

In digital systems, colour is typically specified by a triplet of integer values (*R, G,* and *B*); thereby quantifying a virtual additive mixture of Red, Green and Blue primary-colour stimuli. The virtual mixture may then be reproduced on-screen using the visually combined output from three (*R, G* and *B*) light generating systems, which then become physical analogues of the component stimuli. The *RGB* triplet specification can also be reproduced by 'subtractive-primary' colour mixing as a surface colour phenomenon using coloured dyes or inks. In this case and in an ideal system, each colorant subtracts exactly a third of the wavelengths from the white light being reflected by the paper or textile material. Respectively, the Cyan or Turquoise ink is the 'minus red' primary, Magenta is 'minus green' and yellow is 'minus blue'. Logically when all three inks are applied together at full depth, the result should be a black. (Berns 2000 c) gives a more detailed and general account of the characteristics and laws of additive and subtractive colour mixing.

On Screen colour

On-screen colour reproduction can be calibrated using the measured CIE *XYZ* co-ordinates of colour patches. The objective is to generate a reversible mapping such that on-screen colours can be specified by their CIE co-ordinates and colours can be reproduced accurately on demand to within a measured just visible difference relative to an input co-ordinate specification. It turns out (Oulton et al 1992 and Oulton et al 1996) that at least for the case of a well set up CRT screen, this objective can be met comfortably by treating the RGB/XYZ relationship as a classic 3X3 non-linear cross dependency as indicated in Section 1 and figure 9.2.

Berns (Berns 2000c) warns however that establishing such a scalable model of light output value, or quantifying appropriately independent models of the component primary channels may be much more difficult in some on-screen colour reproduction systems.

The successful method, which involves decomposing the non-linear cross dependency into its non-linear scalar and linearly cross dependent components, was first published in the early 1990s (Oulton et al 1992). The procedure was later tested more extensively as reported in (Oulton et al 1996), where it was shown to enable an improvement in calibration accuracy by a factor of at least five.

The overall nonlinear cross-dependency of screen colour CIE *X, Y, Z* co-ordinates on digital gun-drive values *R, G, B* may be expressed as follows:-

$$\begin{aligned} X &= f_1(R,G,B) \\ Y &= f_2(R,G,B) \\ Z &= f_3(R,G,B) \end{aligned}$$ Where each function $f_1 \,.\,.\, f_3$ acts as a three-dimensionally cross-dependent component of the overall relationship that is potentially nonlinear relative to *R, G, B*. (14)

In order to resolve relationship (14) into its scalar and proportionately cross-dependent components, unit value re-scaling functions are first specified in each dimension *R*, *G*, *B* as in Figure 9.2. Functions are specified whose products R', G', B' may be simultaneously linearized relative to CIE *Y* and equated numerically.

In the current three-dimensional case the relationship is constrained such that:-

$$\begin{aligned} R' &= a_1 * f_4(R), \\ G' &= a_2 * f_5(G), \\ B' &= a_3 * f_6(B), \end{aligned}$$ And the equivalence $R' = G' = B' \Leftrightarrow X = Y = Z$ holds true for all R', G', B'. (15)

In relationship (15), the cross-dependent elements of relationship (14) are held constant; $f_4 \,.\,.\, f_6$ quantify potentially nonlinear single dimension scalar transformations that map cause onto effect in each dimension; and the constants $a_1 ... a_3$ are quantified by measuring the monitor white point.

A re-definition of unit-value is thus established, which maps the device dependent scaling of gun-drive *R, G, B* values onto the implicit Trichromatic or T-Unit scaling of the CIE *X*, *Y*, and *Z* tristimulus value co-ordinates. This in turn enables the development of a linear matrix quantification of the cross dependency as described by W.N. Sproson in his book ‘Colour science in television and display systems’ (Sproson 1983). The relevant descriptive matrix is derived from the CIE Chromaticity co-ordinates *x, y, z* of the individual single gun screen colours where:-

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \qquad (16)$$

X, *Y*, and *Z* denote CIE Standard Observer tristimulus values, and the measured single gun colours and white point are represented as in the following Table:-

colour	Chromaticity Co-ordinates		
red	x_1	y_1	z_1
green	x_2	y_2	z_2
blue	x_3	y_3	z_3
White point	x_n	y_n	z_n

The white point balance constants $a_1 \ldots a_3$ from relationship (15) are now quantified by simultaneous equation, such that relationship (17) below relates the characteristic red green and blue gun-colour chromaticity ratios to the white point $x_n : y_n : z_n$ ratio.

$$\begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{bmatrix} * \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} x_n / y_n \\ 1 \\ z_n / y_n \end{bmatrix} \tag{17}$$

The constants $a_1 \ldots a_3$ thus established re-balance the overall relationship between the unit output values R', G', B' from relationship (15) and the CIE XYZ trichromatic or T-Unit values as follows:-

$$\begin{bmatrix} a_1 x_1 & a_2 x_2 & a_3 x_3 \\ a_1 y_1 & a_2 y_2 & a_3 y_3 \\ a_1 z_1 & a_2 z_2 & a_3 z_3 \end{bmatrix} * \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{18}$$

The grey scale tracking process

In principle, the definition of the unit value re-scaling expressed symbolically in relationship (15) is both functionally distinct and potentially nonlinear in each dimension R, G, B of colour generation. We therefore need to establish by practical experiment that the R', G', B' output values of the tracking process have been linearized relative to Y, and that the validating constraint $R' = G' = B' \Leftrightarrow X = Y = Z$ holds for all R', G', B'. Put another way, we wish to confirm firstly that the visual neutrality of the white point definition x_n, y_n, z_n is exactly replicated at all gun-drive levels, and secondly that a true linear model has been generated. In practical terms this means that the R', G', B' values must first be precisely equated at an additional representative set of perhaps 12 functional definition points on the grey scale. The grey scale tracking process is in effect both a comprehensive evaluation of relationship (15) and a direct implementation of its validating constraint. The point is that when the grey scale tracking is exact at all levels, the scaling of R', G' and B' then becomes a true constant as required by the axioms of multi-dimensional addition in a vector space. Under a constant scaling that satisfies these axioms, the matrix of proportionality ratios in relationship (18) then also becomes a verifiably distinct and independently quantifiable constant within the overall equation system symbolized by relationship (14).

In effect, the proportionate and scalar components of relationship (14) are now fully resolved both analytically and experimentally. They can therefore be represented by independently quantifiable sub-component models derived from independently measured data sets.

The key difference from Gamma based response linearization is that the constancy of scaling over all dimensions that is an essential prerequisite of accurate prediction by vector sum is no longer theoretically assumed, it is established by direct experiment in each dimension.

The first step in the grey scale tracking process requires on-screen gun drive balance to be calibrated against the property of visual balance that is modelled by the CIE co-ordinate equivalence $X = Y = Z$. In the relevant practical experiment, a look up table of R, G, B gun-drive values must be recorded, and each entry must quantify a match to the grey scale. In the second step both Bessel and Spline functions may be used successfully to model the functions $f_4 \, . \, . \, f_6$ of relationship (14). Each of these three mapping functions must be optimized by adjusting its curve fitting parameters relative to the R', G', B' values in the look up table derived in step 1, and the optimization proceeds by any convenient down-hill-search error minimization until all three curves pass simultaneously through each point on the grey scale calibration axis.
Note that on screen, this axis may have a chromaticity x_n, y_n, z_n that is dependent on the current white point setting; the R', G', B' values must therefore be appropriately balanced via relationships (15), (17) and (18). The calculation via the constants $a_1 \ldots a_3$ will work for all local white point settings, but it is better practice to pre-set the screen chromaticity to that of a Standard Illuminant white such as D65 or D50.

Note that in principle the calibration will correctly establish a virtual white point and grey scale for any chosen x_n, y_n, z_n chromaticity but if the white point at gun max R = G = B is not close to this point, increments at the top of one or more gun-drive scales may be lost with consequent reduced gamut.

Note also that a badly set or intrinsically poor screen black point at gun-drive R = G = B = 0 is likewise sub optimal.

2.3 Colour profile characterization.

Another colour quantifying discipline that is often used in imaging and colour reproduction is called ‘device profiling’. A device profile is an essentially fixed characterization that is typical of and specific to a particular model and make of colour scanner, camera, computer screen or colour printer. Pre-measured profiles are widely available, and their main function is to enable transformations between sets of device specific colour co-ordinates. They also enable the resolution of inter device compatibility problems where the chosen colour may lie outside the gamut of reproducible colours for a given device. ‘ICC (International Color Consortium) device profiling’ is a widely accepted and used implementation of this concept that is gradually developing into a comprehensive and accurate model (see ICC 2008 and http://www.color.org) .

A typical user reaction to the device profiling approach is given at http://www.drycreekphoto.com/Learn/profiles.htm.

Full current-state colour calibration functions that systematically update the basic characterization can clearly be added to the device profiling system. Calibrations of this type allow for such factors as local device adjustments or ageing or something as simple as the effects produced by a change of ink or paper supplier.

2.4 Colour appearance modelling

Colour models are also under active research that seek to explain the subtleties of ‘colour in context’. The research objective is typically to simulate the changes in colour appearance that occur when the viewing context is changed (Fairchild 2005). The change may be in the light source used to illuminate the scene, the effect of adjacent colours and the wider ambient context, or perhaps the changes that are related to surface texture differences. The best known model is called CIECAM 97, the most recent one to be adopted is CIECAM 2002, and both of these models are discussed in detail in (Fairchild 2005).

3. A case study in colour communication

In recent decades the opportunities for gaining advantage by modelling colour have increased significantly in parallel with the rapidly expanding use of media such as colour TV and video, on-screen and internet computer colour, and the wide availability of cheap colour printing. Take for example the case of the abundant and remarkably cheap clothing that we expect to be supplied in very large volumes by the retailers of mass market fashion.

Typically, the consumers will expect the store to stock new colours that change frequently and reflect the seasons. They will look for and buy the colour that currently most appeals to them, and they will be led in their choices at least in part by the ‘in colours’ of fashion predictions. They are likely to buy multiple colour co-ordinated accessories to these outfits if they are available. They exhibit very subtle colour preferences, and it has been shown in a test marketing exercise (Marks and Spencer 1991) that in a given garment style and quality, one specific version of the colour described as Navy Blue consistently outsold all of the tested alternative versions by a factor of ten to one. They will also complain about and reject retail outlets and products that have poor colour ranges or include visibly mismatching garment components.

Models that enable optimized colour communication are thus typically required, when the need is:-

1. To be in close touch with current colour fashions in the target market segment.

2. To select, develop, and deliver seasonal colour ranges for the chosen market at least four and perhaps eight or more times per year, with the shortest possible lead time.

3. To specify the desired colour range precisely and manage its implementation in large volume production. Taking a lingerie-set as an example, this might involve co-ordinating the colour of 20 or more distinct components (both textile and non-textile), in successive stages of production, at multiple remotely sited production units.

4. To establish quality control systems that are capable of monitoring colour fidelity and continuity from batch to batch in production, and from the original design concept to the retail sales counter.

The simple answer is of course to give up any attempt to meet such requirements, other than by simply optimizing your choice of suppliers, and selling what is on offer at their wholesale warehouses. However consider Figure 9.4, where all the relevant stakeholders and participants are assumed to be in direct communication by electronic networking.

Insert Fig 9.4 near here

Figure 9.4 illustrates the key dialogue channels and the diverse colour modeling requirements diagrammatically. The resultant creative, colorimetric, and technical colour communication links can be provided by internet portals which are password and subscription protected. The first key advantage of a communication network is that communicating by electronic links is easy and instantaneous. This basic capability is delivered by the hardware of the computer network, a text description model called HTML (the ‘hypertext mark up language’) and the data mark up language XML (the ‘extended mark up language’). In combination these agreed protocol models enable universal inter computer communication using text and images. Before useful colour communication can take place however, appropriate colour visualization, specification, calibration, and match prediction modeling systems must also be present. It is additionally necessary to enable and standardize the physical measurement and spectral definition of all the colour stimuli involved; and to standardize the calculations whereby these models predict colour matches and colour differences. See also the reference (ASTM 2008).

3.1 The specification of colour identities, matches, and tolerances

Colorimetry is conventionally standardized by reference to the CIE system, but some users of the colour communication network will neither need to know the relevant colorimetric technicalities, nor would they understand them. They may alternatively identify a given component of the colour range by a colour name, ID number, or even perhaps by a production order number. It follows that the precise colorimetric technicalities and calculations should be implemented in a hidden layer of the model, using callable subroutines whose output is only displayed on demand.

3.2 Quantifying and visualizing the creative input to colour range development.

The concerns of, and methods used by creative colourists are quite distinct from those of the technical colourist, dyer, colour systems managers and the quality control team. The work of the creative colourist is essentially visual, and it uses input from fashion predictions, colour libraries, sales monitoring and both physical and virtual product prototyping in order to assemble and define new colour combinations and product colour ranges.

These essentially visual processes can also be aided significantly by colour modeling, and two closely inter-related and interacting colour models are needed. One of these models must implement and enable the essentially artistic work flow of the creative team, and provide the users with comprehensible and appropriate tools for creating, manipulating and visualizing colours. The other component must be comprehensible to the technical colourist, and generate the required unambiguous spectral curve and CIE co-ordinate definitions for all the colours being discussed and visualized. The term comprehensible is deliberately used twice here. This is because the relevant colour models must collaborate electronically in order to bridge the often significant communication gap between the creative developers of the colour range and the technical managers and producers of coloured products. In effect, what is needed is a computer aided design or ‘CAD for colour’ system.

The objectives of such creative systems include:-

1. Providing the user with extensive colour-calibrated models including colour libraries and virtual product simulations, that can be shared electronically by members of the development team.

2. Allowing the users to visualise explore and develop sympathetic colour combinations, such as print colour ways and seasonal colour ranges as a whole rather than by piecemeal colour changes.

3. The ability to specify all of the visualized colours technically (using spectral curves and CIE colour co-ordinates), so that they can be reproduced accurately as products.

The pay-back for developing and using such colour networking models is typically a dramatic reduction in both the cost and the lead times necessary for developing new colour ranges (see Oulton et al 1996). A significantly enhanced flexibility of response to fashion changes and consumer preference is also enabled.

A key factor in all such colour imaging and product visualization systems is the use of calibrated colour imaging, colour reproduction devices and device profiling (see section 4.2). The need for precise electronic colour visualization and specification is clear when you understand the potential that exists for finding a subtle variant of say Navy Blue, Raspberry or Lavender, which could outsell all the other variants by ten to one.

3.3 Mark up and information transmission languages for describing colour.

A mark up language embeds a set of computer instructions or tags in the content of a given image or text file. The name of each tag is specific and it tells the receiving computer how to treat the following section of file content. In the case of a document file, an example would be a tag that specifies the chosen font, or font size, or page layout.

There are three key problems when defining a mark up language model. Firstly, it must be universally understandable to those who wish to use it. The intent is typically to establish a standard that is accessible to all, and the language must therefore have a fully standardized and published ‘schema’ (such as that for XML) that defines the semantic meaning, syntax and vocabulary of the language.

Secondly, the language must be both comprehensive and accurately descriptive, because computers are completely unintelligent, and cannot ‘talk their way around’ difficulties of semantics, syntax or vocabulary as humans might do.

Thirdly, the language must have complex data omission and error handing features, with robust default values. This allows the message-receiving interpreter to act competently on fragmentary or incomplete data.

An example of an openly accessible colour oriented mark up language is the CxF, (or ‘Colour Exchange Format’) language pioneered by Gretag-Macbeth (CxF 2002). This is a good example of a formatting language whose structure and content (which are written as an extension to the standard XML schema) are freely accessible to potential users. CxF is however only one attempt to solve the problems of colour communication, and a number of alternative approaches are either under current research or technical discussion (see Section 4 for further guidance on learning about and adapting mark up languages for use in colour modelling.)

3.4 Quantifying colorant formulations, and predicting optimum colour mixtures

Once the colour specifications are agreed, the task of selecting an optimum colorant recipe for a given textile product is typically delegated to the dyer or technical colourist, who will usually be supported by a proprietary computer colour-match prediction system. The relevant software will be installed with a database of spectral curves for a large range of potentially useful dyes, and it will be capable of evaluating and minimizing the problems associated with metameric matches. This colour recipe prediction system will use a complex nonlinear search in *N* spectral dimensions that depends critically on the 'Kubelka Munk' model (see Berns 2000). This relates the amount of light reflected by a coloured object to the concentration of the colorants present. The recipe prediction model will probably also use an iteratively convergent recipe refinement algorithm originally published by Allen (see Berns 2000). Readers who seek to create such models are recommended to refer in the first instance to 'Billmeyer and Saltzman's principles of color technology' (Berns 2000), where a wide ranging annotated bibliography of source material for building such models is made available.

3.4.1 Colour matching to physical or numerically specified samples

In traditional textile dyeing the colour match is usually made to a physical sample of the target colour. Ideally this sample would be a piece of the same fabric to be dyed, and it should have a measurable spectral curve that can also be used as a basis for minimizing metameric match problems. However, in a major industrial trial in the early 1990s a change from physical samples to standardized numeric colour definitions was shown to contribute significantly to minimizing 'colour standard drift', to improving product colour continuity, and to improving the fidelity of the final product to the original design inspiration.

The technical colourist will in practice also have concerns such as cost minimization and dye fading resistance. Recent proprietary computer software systems for predicting dye recipes often now include predictions of washing and light fading properties, and they also support recipe cost optimization. On-screen computer visualization for the predicted but as yet undyed alternative dye recipes is also gaining in popularity. In such systems (see Figure 9.4) calibrated colour appearance models are established as 'virtual dyeings' and these can at least partially replace physically dyed 'lab dip' samples during colour range development (Oulton et al 1996).

3.4.2 Colour Libraries

Due to the cost of colour range development, it makes good sense to seek maximum benefit from each successfully developed colour standard, and maintaining a detailed inventory of previously successful colour definitions is a rewarding solution. When such a database is combined electronically with an appropriately colour oriented and preferably visual indexing system, it has been shown that as often as nine times out of ten it is possible to find an existing recipe immediately that is an acceptable match.

4. Future trends in colour modeling

All aspects of colour modelling are expected to continue to develop significantly, and some advances will probably reflect developments in numeric analysis techniques. Axiomatically verifiable vector space models that include one or more data linearization steps are also likely to be developed, particularly in order to explain and characterize the complex scalar properties of phenomena such as colour difference. Further progress in colour-communication related models is expected, and new models may be developed for example by adding technical colour description and colorimetry extensions to hypertext languages such as HTML or XML.

An expected outcome of these developments will be significant advances in imaging and colour reproduction, particularly of complex surface textures such as those of textile materials. The demand for the enabling colour models is expected to be significant, and it will be driven by the available commercial advantages anticipated in Sections 2 and 3.

4.1 Trends in the available tools and methods

Colour modelling problems, particularly in vision science and colour appearance modelling, often concern phenomena in which the number of interacting variables is uncertain, or their patterns of interaction are currently unknown. It follows that the methods and tools of multi-variate and numeric analysis are key elements in colour modelling. It also follows that the multi-dimensional nature of the sensation will be amenable to geometric description and vector space modelling. Those involved in colour modelling will typically need to be mathematically adept and may need to use Affine and Riemannian geometry as well as the perhaps more familiar Euclidean geometry of Newtonian physics in order to model ‘colour space’ (Wyszecki 1982).

The best approach in many such cases is to treat the phenomenon in question as a ‘black box’ operation that transforms inputs into outputs. The properties of such ‘black box systems’ may be analysed by altering their inputs systematically while closely studying their outputs. Four examples typify this approach and may be useful in colour modelling. They are neural network modelling (Golden 1996), clustering analysis and simulated annealing (Arabie et al 1996), Principle Component Analysis or PCA (Jollife 2002) and wavelet analysis (Torrence et al 1998).

Principle Component Analysis, also sometimes known as the Hotelling transform, or orthogonal decomposition is a technique that allows the apparent dimensionality of a descriptive dataset to be reduced. The relevant exploratory analysis involves the calculation of the eigenvalue decomposition of a data covariance matrix, or the singular value decomposition of a data matrix (Jollife 2002). This technique is a key tool in some recent colour related journal articles, and it is expected to receive significant attention in future colour modeling projects.

Simulated annealing is a useful approach when seeking global minima in the multi-dimensional data spaces typified by spectrally defined data and metameric equivalence. Clustering analysis is helpful when analysing the apparently noisy data sets that are generated in visual experiments.

Wavelet analysis is a relatively recent development in the wider field of Fourier analysis, and it allows sequentially ordered datasets with time and /or spatially dependent characteristics to be analysed. It is particularly useful when the functional relationships under analysis have discontinuities or sharp peaks. Combinations of rapidly decaying short duration wavelets each of which has a distinct wavelength and initial amplitude are used to model and predict the relevant properties (Torrence et al 1998). Wavelet analysis has been applied successfully to photographic images, particularly of textile structures, and a significant number of journal articles have reported interesting results using this approach.

Modelling the colour sense

The problem with modelling the human colour sense is threefold. Firstly, the phenomenon is caused by an N dimensional set of spectral power inputs that all appear to cause nonlinear responses. Secondly, the visual response appears to be a multi-layer phenomenon with both parallel and sequentially acting component responses; and thirdly, the visually distinct colour sensations cannot necessarily be treated as individual responses because they often appear to exist only as complex colour appearance interdependencies.

The term affine geometry refers to a multi-dimensional descriptive system of proportionate or ratio values with a strictly constant but not necessarily fully defined scalar metric. The term is rarely if ever used in the literature in connection with the CIE colorimetric model; however from the outset the pioneers of colorimetry appear to have intended their model to consist of a set of demonstrably valid affine rescaling and axis transformations based on ratio value datasets. The undoubted predictive success of the resultant CIE colorimetric transform appears to validate affine geometry and affine vector space transformation as potentially useful approaches to colour modelling. The key to the potential success of this approach is that the axioms of affine transformation establish a fundamental distinction between on one hand the proportionation ratios of multi dimensional vector addition, and on the other hand the unit value scaling that establishes the measure of spatial separation or colour difference within each dimension of colour space. Multi-dimensional affine constructs and sets of single dimension nonlinear projections of scalar value are thus recommended as a potentially useful colour modelling tools, and as a basis for future extensions of the existing CIE colorimetric models.

Colour Measurement

The general principles and practical aspects of laboratory and industrial ‘colour measurement’ are well described in Berns 2000. The term ‘colour measurement’ is placed in quotes to remind the reader that only the relevant physical stimuli can actually be measured, and the visual response definition is the product of some colorimetric model, usually the CIE colorimetric transform. For those who wish to implement the CIE colorimetric model themselves, the book by Westland and Ripamonti (Westland 2004) is available. This is a particularly useful source of fully annotated and tested calculation subroutines which are recommended as a basis for implementing the CIE models. Each subroutine is denoted in MATLAB, which is a mathematical modelling language that is essentially an extension of C++.

The publications by the CIE and the ASTM (CIE 2008, and ASTM 2008) are also obligatory source material references when implementing fully annotated and traceable CIE models.

4.2 Trends in colour description, definition and colour communication methods

Those interested in extending mark up languages such as XML as a basis for colour modelling might perhaps start by studying a not necessarily definitive colour related example, see (CxF 2002).

The general trends in mark up language development are best understood by visiting the authoritative and comprehensive website of the W3 consortium (W3schools 2008). HTML concerns data presentation and visual formatting, whereas XML is a more flexible general purpose description language for describing data structure and data content (see also section 3.3). The current situation regarding extensions of XML for describing colour is somewhat unclear, but an ultimate winner will no doubt emerge and it is expected to provide a solution that is both commercially and scientifically important.

5. Commercial vendors and their products

Konica Minolta. Konica Minolta concentrate on providing high quality instrumentation, cameras and colour reproduction hardware, the UK contact address is:-
Konica Minolta Sensing Europe
UK Branch Office Suite 8
500 Avebury Boulevard
Milton Keynes
Buckinghamshire
MK9 2BE

Telephone: +44 (0)1908 540622. Internet: http://www.konicaminolta.eu

X-Rite Inc. X-Rite first entered the market for colour related instrumentation and products only in 1990, but they have now become a major international vendor, and in the UK the address is:-
X-Rite Ltd,

Acumen Centre,

First Avenue

Poynton, Cheshire,

SK12 1FJ, UK.

Telephone +44 (0) 1625 871100.

Datacolor Inc. Datacolor are well known and established as suppliers of colour related instrumentation and software solutions for the global textile and apparel industries. They are also pioneers of colour calibrated on-screen visualization for textile products, and their contact details are:-

Datacolor Ltd

6 St Georges Court,

Dairyhouse Lane,

Broadheath,

Altrincham,

Cheshire WA 14 5UA.

URL: http://www.datacolor.com
Email: postmaster@datacolor.com

Sony Corporation. Sony, who are well known as Japanese global vendors of electronics and media products, are notable in the colour modelling field for their high quality Trinitron colour screen products. Their contact details are:-

SONY BROADCAST & PROFESSIONAL

Jays Close, Viables
Basingstoke, Hampshire
RG22 4SB, UK
Phone: +44 (0)1256 355011
http://www.sony.co.uk/

eWarna. eWarna www.ewarna.com/is a pioneering Malaysia based company that sells software-only colour solutions. Their products are aimed specifically at the users of colour on the internet. eWarna have entered into a partnership with an industry-specific business-to-business website operator, Hangzhou Hi2000 Infotech Co Ltd in China to market its services to enterprises in that country.

Hangzhou Infotech can be found on http://b2b.chemnet.com.

Chromashare Ltd. Chromashare www.chromashare.com is also a software solutions vendor. They offer products that enable precise colour communication over the internet, and are represented in the USA by ‘Precision textile color’ http://www.precisiontex.com/. The offered overall solution is notable for its use of the ‘colour server concept’, and the use of a comprehensive proprietary colour description language to enable simple and accurate colour communication.

ChromaShare's desktop application CS SmartClient delivers its functionality through ‘web services’ and collaborating users thus establish global availability at all times for their colours and their product specifications. Colour calibrated web browsing is also supported.

The postal address and contact details for Chromashare Ltd are:-

Chromashare Ltd
18 Lincoln Place
Hulme St
MANCHESTER M1 5GL,
Tel: +44 (0)161 237 3046.

6. References

Arabie et al 1996: ‘Clustering and Classification’, Editors P.Arabie, L.J. Hubert and G. De Soete. Published 1996 by World Scientific Press, New Jersey, USA.

ASTM 2008: The American Society for Testing and Materials, now known as ASTM International , (www.astm.org) Address : 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428 – 2959, USA. The ASTM works to improve standardization in colorimetry, and publishes widely accepted standard procedures and methods for measuring the spectral reflectance of coloured surfaces. It also certifies the required data tables and methods, for use when calculating colorimetric values such as CIE colour co-ordinates.

Berns 1997: R. S. Berns, "A Generic Approach to Color Modeling". *Col. Res. & App 1997 No 5* pp 318-325. Publ. Wiley Interscience New York.

Berns 2000: Billmeyer and Saltzman's Principles of Color Technology, Third Edition, Editor Roy S. Berns, published by John Wiley & Sons, New York. This is an authoritative reference source for deeper study.

Berns 2000a: Standardized Illuminants: Berns 2000, Ch1, Section B, pp 3 – 10

Standard Observer systems: Berns 2000, Ch2, Section C, pp 50 – 54.

Standardized visual inspection: Berns 2000 Ch3, Section C, pp 78 – 82

Berns 2000b: The CIE colorimetric system: Berns 2000, Ch2, Section C, pp 44 – 63

Berns 2000c: Absorptiometry: Subtractive colour mixing in clear solids and liquids: Berns 2000, Ch6, Section B, pp 151 – 158.

CIE 2008: The CIE Central Bureau: Address, Kegelgasse 27, A – 1030, Vienna, Austria, is the primary standardizing body for Colour. The CIE recommends the precise way in which the basic principles of colour measurement should be applied, and CIE Publication 15:2004 "Colorimetry" is the latest edition of one such set of recommendations. CIE publication15:2004 contains information on standard illuminants; standard colorimetric observers; the reference standard for reflectance; illuminating and viewing conditions for visual colour matching; the calculation of tristimulus values, chromaticity coordinates, colour spaces and colour differences; and various other colorimetric practices and formulae. The CIE explicitly warrants that publication15:2004 is consistent with the fundamental data and procedures described in the CIE Standards on colorimetry.

A full list of CIE publications is available at http://cie.kee.hu/newcie/framepublications.html

CxF 2002: CxF white paper 1.0 June 2002. Published by X-Rite Gretag-Macbeth. Available at http://www.color-source.net/en/Docs_Formation/CxF_Public_Whitepaper-V1-01.pdf

Dry Creek Photo 2008: For an informative and interesting 'users view' of ICC colour profiling, visit the website at http://www.drycreekphoto.com/Learn/profiles.htm

Fairchild 2005: M.D.Fairchild, 'Colour appearance models' 2nd Edition. Published in 2005 in the Wiley – IS&T Series in Imaging science and technology, Chichester UK.

Golden 1996: Richard M. Golden, 'Mathematical methods for neural network analysis and design' 1996, Published by MIT Pres Cambridge MA, USA.

Halmos 1974: P.R.Halmos, 'Finite-dimensional vector spaces'. Published in 1974 by Springer – Verlag New York.

ICC 2008: The International Color Consortium. Address, 1899 Preston White Drive, Reston VA, 20191 USA, and at their website http://www.color.org/index.xalter

Jollife 2002: I.T. Jollife, 'Principle Component Analysis', 2nd Edition. Published by Springer Science and Business Media, New York USA, and Berlin Germany.

M&S 1991: Marks and Spencer confidential customer-preference research. Private communication, C.Sargeant 1991.

Oulton et al 1992: D.P.Oulton and I Porat 'The control of colour by using measurement and feedback'. Journal of the Textile Institute Vol 83 No.3 1992, pp 454 – 461.

Oulton et al 1996: D.P.Oulton, J.Boston, & R.Walsby, "Building a Precision Colour Imaging System". Proceedings of the IS&T/SID 4th Color Imaging Conference. Scottsdale Arizona, pp14-19 Nov 1996. Published by IS&T – The Society for Imaging Science and Technology: Address, 7003 Kilworth Lane, Springfield Virginia 22151 USA.

Oulton 2009: D.P.Oulton 'Notes toward a verifiable vector algebraic basis for colorimetric modeling'. Accepted March 2008, for inclusion in Color Research and Application VOL 33, to be published by Wiley Interscience New York.

Sproson 1983, W.N.Sproson, 'Colour science in Television and display systems', Ch 2 pp 27 – 29, Published 1983 by Adam Hilger Ltd Bristol England.

Torrence et al 1998: C.Torrence and G.P.Compo, 'A practical guide to wavelet analysis', Bull. Am. Met. Soc. Vol. 79 No.1 Jan 1998, pp 61 - 78 Published by the American Meteorological Society, Boston USA.

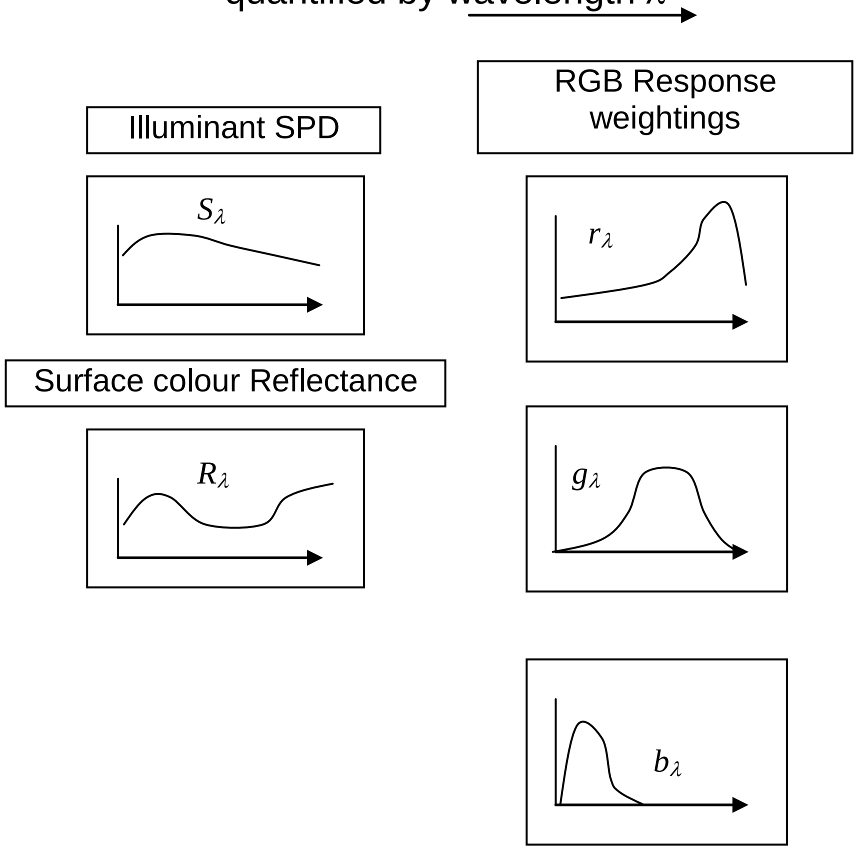
W3schools 2008: The indicated site (http://www.w3schools.com) is dedicated to explaining and defining the many distinct languages, protocols and definitions that make the internet work, and all of the relevant concepts are covered by detailed tutorials. Concepts covered other than XML and HTML, include DTD (the pro-forma for ‘document type description’) and XSL (the ‘extendible style-sheet language’) that defines the relevant semantic styling templates),

Westland 2004: S.Westand and C.Ripamonti, ‘Computational colour science using MATLAB’ Published 2004 by John Wiley and Sons Inc., New York and London.

Wyszecki 1982: G. Wyszecki and W.S. Stiles, ‘Color Science, Concepts and Methods’, Second Edition © 1982 by John Wiley and Sons Inc., New York and London. It was also re-published in 2000 without further significant editing in their Wiley classics library edition.
This book is regarded by many in the field to be the primary reference source of colour science. It is a fundamental repository and exposition of the historical development of colour science, and of the available concepts and methods of colour modeling up to the publication date. However it inevitably lacks any input on more recent topics such as colour appearance modeling, and imaging science. It is also a somewhat ‘heavy read’ for non specialists.

MAPPING FROM CAUSE ONTO EFFECT BY VECTOR SUM

The cause has *N* defining elements or dimensions quantified by wavelength λ



$N \Rightarrow 3$ Mapping by vector sum

Weighted R', G', B' colour co-ordinate description of effect

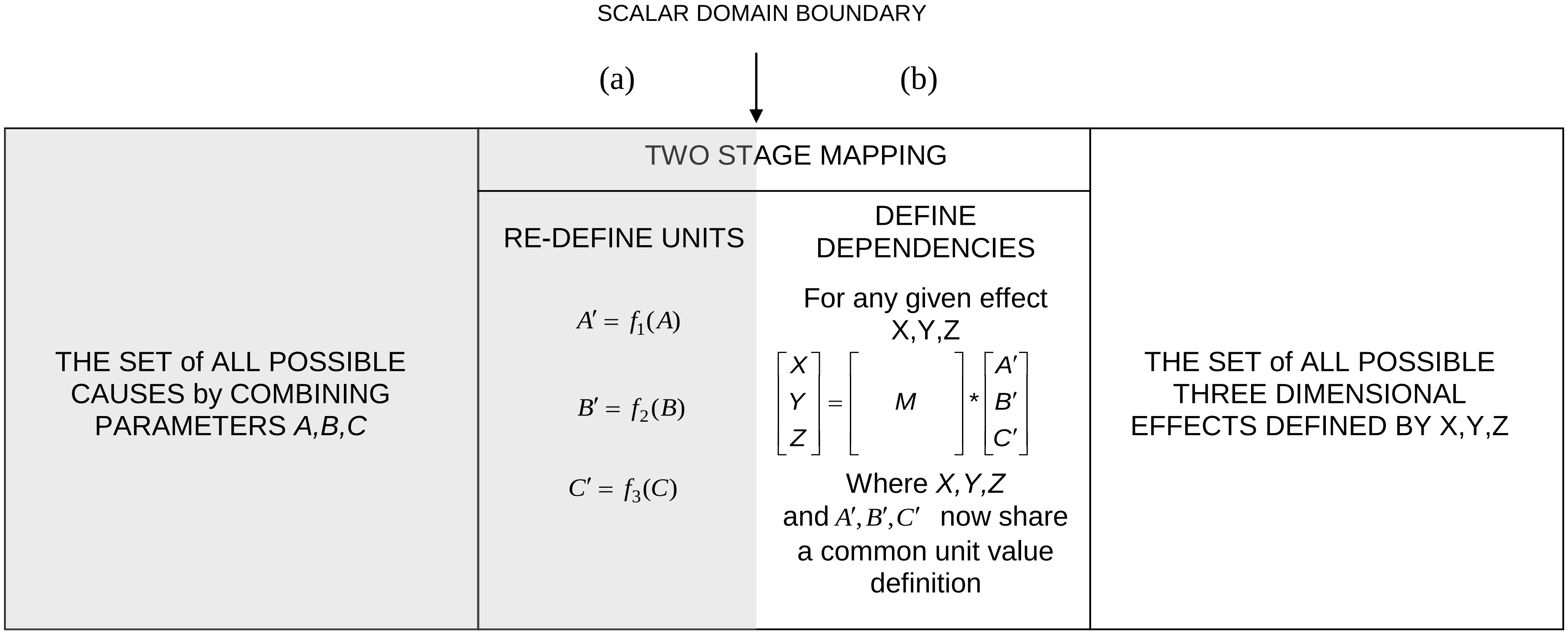
$$\sum_{\lambda=N}^{\lambda=1} S_\lambda . R_\lambda . r_\lambda \Rightarrow R'$$

$$\sum_{\lambda=N}^{\lambda=1} S_\lambda . R_\lambda . g_\lambda \Rightarrow G'$$

$$\sum_{\lambda=N}^{\lambda=1} S_\lambda . R_\lambda . b_\lambda \Rightarrow B'$$

Figure 9.1.: The *N to 3* mapping by linear vector sum that is used to predict metameric visual matches, where *N* represents some arbitrary number of subdivisions of the visible spectrum.

FINDING THE LINEAR MODEL by 3-DIMENSIONAL MATRIX MAPPING OF CAUSE ONTO EFFECT



SCALAR DOMAIN BOUNDARY

(a)

(b)

THE SET of ALL POSSIBLE CAUSES by COMBINING PARAMETERS *A,B,C*

TWO STAGE MAPPING

RE-DEFINE UNITS

$A' = f_1(A)$

$B' = f_2(B)$

$C' = f_3(C)$

DEFINE DEPENDENCIES

For any given effect X,Y,Z

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \quad & M & \quad \end{bmatrix} * \begin{bmatrix} A' \\ B' \\ C' \end{bmatrix}$$

Where *X,Y,Z* and A',B',C' now share a common unit value definition

THE SET of ALL POSSIBLE THREE DIMENSIONAL EFFECTS DEFINED BY X,Y,Z

Figure 9.2.: Illustratively, a 3X3 non-linear cross-dependency can be resolved using a two stage mapping, where the set of intra-dimensional scalar redefinitions as in relationship (a), enables the linear cross dependency to be quantified by means of a constant matrix M of proportionality ratios as in relationship (b).

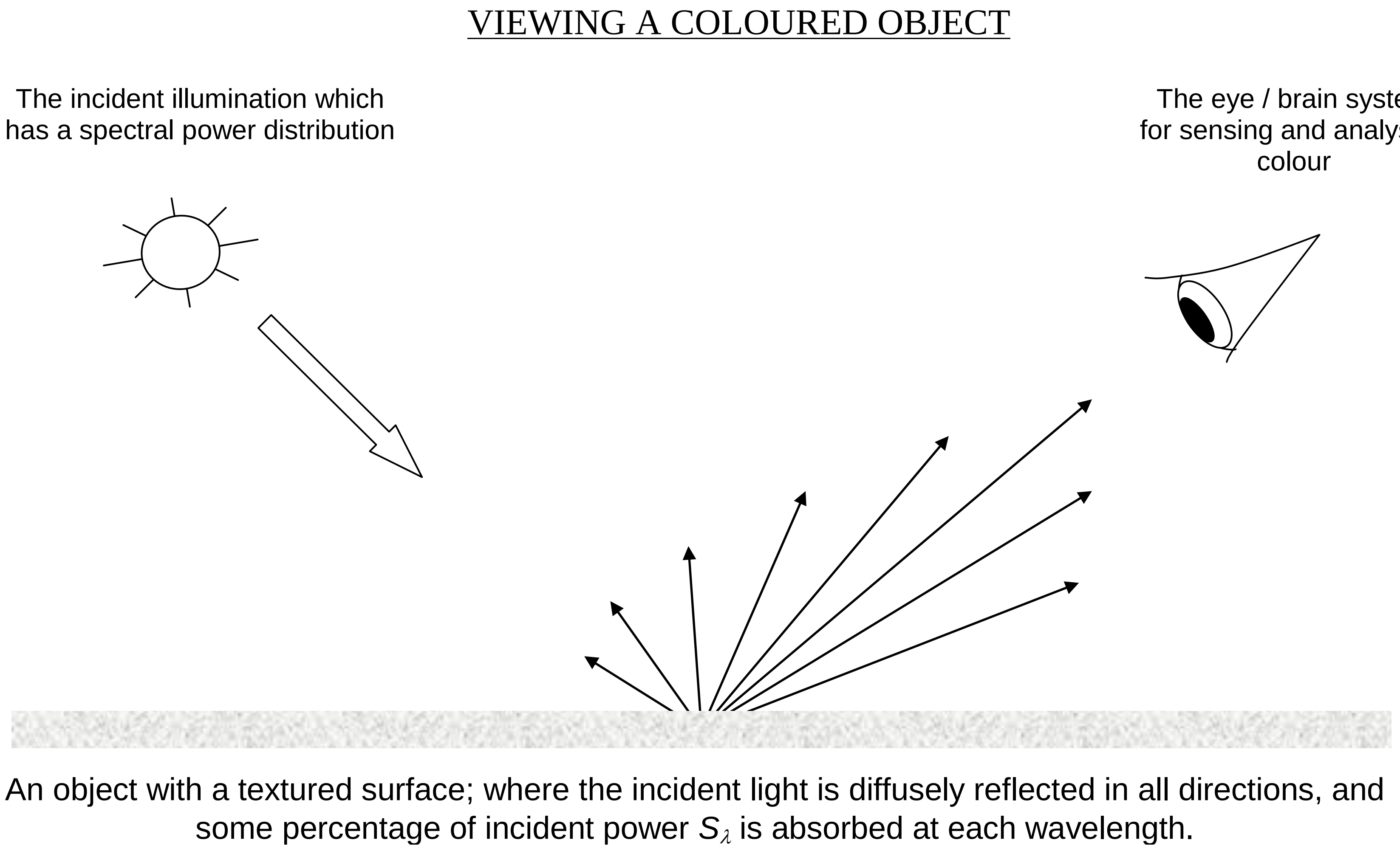
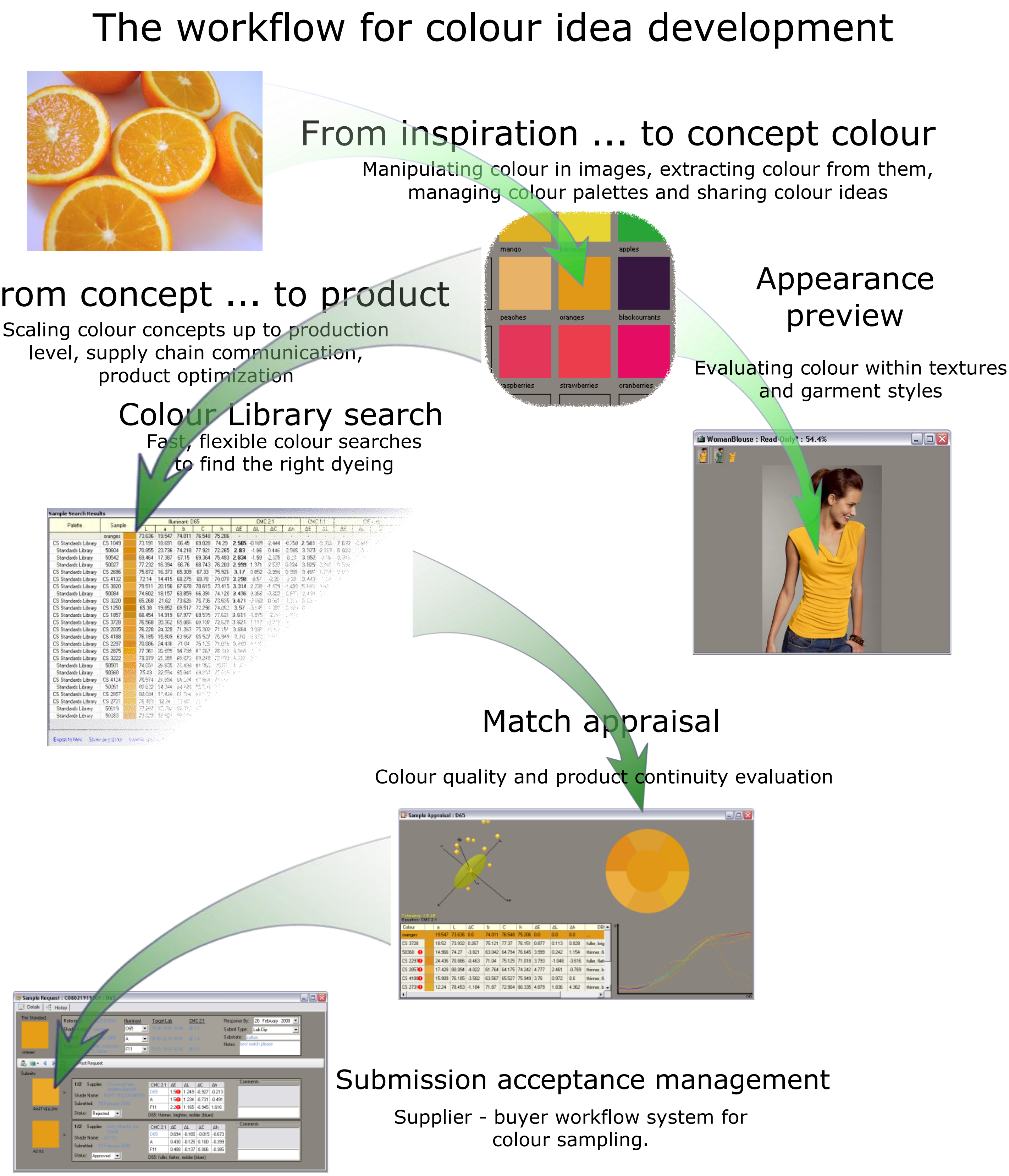


Figure 9.3: The three defining factors of the object-colour sensation.



The workflow for colour idea development

From inspiration ... to concept colour

Manipulating colour in images, extracting colour from them,
managing colour palettes and sharing colour ideas

Appearance preview

Evaluating colour within textures
and garment styles

From concept ... to product

Scaling colour concepts up to production
level, supply chain communication,
product optimization

Colour Library search

Fast, flexible colour searches
to find the right dyeing

Match appraisal

Colour quality and product continuity evaluation

Submission acceptance management

Supplier - buyer workflow system for
colour sampling.

Figure 9.4. Some key work flow sequences and colour communication links that are present during the development of new coloured textile products are highlighted and typical data management and communication tasks are identified at each stage. © Chromashare Ltd.