COMPUTER MEDIATED COLOUR FIDELITY AND COMMUNICATION

by

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Dedication

To my mother and father.

Acknowledgements

I would like to express my appreciation to my supervisor, Professor Stephen Scrivener, for his support and encouragement throughout the course of this research; and to Professor Ernest Edmonds, Dean of the School of Pure and Applied Science, who directed my research.

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Computer Mediated Colour Fidelity and Communication

ABSTRACT

Developments in technology have meant that computer-controlled imaging devices are becoming more powerful and more affordable. Despite their increasing prevalence, computer-aided design and desktop publishing software has failed to keep pace, leading to disappointing colour reproduction across different devices. Although there has been a recent drive to incorporate colour management functionality into modern computer systems, in general this is limited in scope and fails to properly consider the way in which colours are perceived. Furthermore, differences in viewing conditions or representation severely impede the communication of colour between groups of users.

The approach proposed here is to provide WYSIWYG colour across a range of imaging devices through a combination of existing device characterisation and colour appearance modeling techniques. In addition, to further facilitate colour communication, various common colour notation systems are defined by a series of mathematical mappings. This enables both the implementation of computer-based colour atlases (which have a number of practical advantages over physical specifiers) and also the interrelation of colour represented in hitherto incompatible notations.

Together with the proposed solution, details are given of a computer system which has been implemented. The system was used by textile designers for a real task. Prior to undertaking this work, designers were interviewed in order to ascertain where colour played an important role in their work and where it was found to be a problem. A summary of the findings of these interviews together with a survey of existing approaches to the problems of colour fidelity and communication in colour computer systems are also given. As background to this work, the topics of colour science and colour imaging are introduced.

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Chapter One

Introduction

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Colour plays a very influential role in our lives, affecting not only the way we see but also our feelings and our actions. Colour pervades both society and our everyday language. (For example, using red to signify danger or "turning green" with envy.) Since ancient times, it has been associated with emotion, religion and magic. Many of us have strong preferences for certain colours, particularly in clothing, and this has been used as the basis for the famous Lüscher personality test [Lusc87a]. Colour is also highly influential in advertising with some minimalist advertisements going as far as to use just colour alone to convey meaning. Similarly, colour is used in packaging to single out individual products which are often all competing for the customer's attention. Colour also has cultural symbolism associated with it; for example, white (being linked with purity and innocence) is traditionally worn at christenings and weddings whilst the Chinese regard this very same colour as being more appropriate for death and mourning.

Over the past few years, there has been a rapid growth in the area of computer technology and recent developments have lead to relatively inexpensive, high-performance colour systems becoming widely available. This has boosted the acceptance of computer aided design (CAD) and manufacturing (CAM) systems and has helped to launch new practices such as desktop publishing (DTP). The range of computer-controlled colour imaging peripherals include colour monitors, printers, scanners and digitisers. As their performance improves, there is a growing demand for good colour fidelity between devices, in particular between screen and print. Indeed, many CAD/CAM users require an accurate match between their screen image and the final product.

One specific area where colour needs are both demanding and changing is in the *textile* business. Here, the ever-changing face of fashion influences both style and colour and ultimately dictates what it sold. Getting the colour right is therefore of critical importance. Colour communication is equally important in such businesses. Often, colour specifiers, designers, manufacturers and clients all work independently but nevertheless need to exchange colour information. This is frequently achieved through the use of physical samples which must be carefully made to match the target colours.

1.2 THE PROBLEM

Unfortunately, the goal of universal high fidelity colour for imaging devices has yet to be realised. Having the same notional colour appear differently on screen, print and any other media involved is not only troublesome, but also confusing for the user of the afflicted CAD/CAM system. Communication is equally problematic; using physical samples is costly, slow (both in the time taken to produce them and also to deliver them) and often ambiguous. Although a lot of effort may be spent to achieve what is regarded as being a close colour match, if the samples are not viewed under precisely the same conditions at the target location, colour misperception is likely to arise.

A number of factors contribute to the cause of the problem. Firstly, colour in computer systems is almost invariably *device dependent*. That is, a given set of colour "values" relate to *one* particular colour imaging device and cannot be directly applied to another. This property arises from fundamental physical differences between devices, in particular for dissimilar media or where different colourants are mixed to produce a particular shade. A second critical factor is *viewing condition dependency*. Colours seen, for example, under tungsten lighting may appear totally different to when they are viewed under daylight illumination. Further factors such as lighting level, background colour, sample size and surface texture all modify the way colour is perceived and hence make the task of colour matching much more difficult.

The problems caused by device and viewing condition dependency also arise when colours are communicated. Furthermore, the problems are exacerbated by the fact that the recipient's devices and viewing environment are likely to be beyond the control of the sender. Another major problem is the language used to communicate colour. There currently exist many different systems for describing colour which may be applied on either a national, industry or arbitrary basis. Again, the chances are that the two parties involved describe colour using different terms and so this often leads to further difficulties. As already mentioned, trying to overcome this using the exchange of physical colour samples can prove to be expensive (due to the cost of sample preparation), slow (the physical samples must be transported) and, more critically, does not address viewing condition dependency.

Although the problems associated with colour fidelity and colour communication are virtually universal for all users of colour computer systems, not all CAD applications actually require a high degree of colour precision. Specific examples of these include electronic circuit layout or engineering design. In such cases, colour may be used to label different information but its precise appearance is non-critical. It should be evident then that the exact requirements of CAD for colour fidelity and colour communication are very much application dependent. Therefore, by focusing on the most demanding of applications, the benefits of improved fidelity and communication can be demonstrated and subsequently applied to less colour-critical areas. Arguably the most challenging domain utilising colour CAD systems is textile fashion design, as already mentioned, since precise colour across different media is essential as is the communication of colour information between the various people involved.

1.3 A PROPOSED SOLUTION

In order to overcome existing limitations in the fidelity and communication of colour in computer-based systems, the solution which is advocated here is to apply existing device characterisation methodology in conjunction with colour appearance modelling. These provide a "portable" representation of colour which is both device and viewing condition independent. In addition, to further facilitate colour communication, it is suggested that multiple colour notation systems be implemented and interrelated mathematically.

While attempts to solve the problem of colour fidelity for computer-based systems do already exist in the form of colour management systems, none of these currently considers colour appearance to any adequate extent. Another potential problem with such systems is in their approach to gamut limitations. In order to make the best use of the available range (or gamut) of colours reproducible on a given colour imaging device, some form of gamut compression (or relative scaling) is frequently applied to all the colours. While this may be perfectly reasonable where the overall objective is to reproduce a photographic image such that it appears "pleasing" (e.g. the sky is blue and flesh tones look right), it is disastrous for those applications where colours have to match one another across different media. In these circumstances, absolute reproduction is required and this is a common requirement for many domains requiring high colour precision, including the textile business. The solution proposed here aims to fill this gap by providing users with "what you see is what you get" colour.

The remainder of this thesis endeavours to justify and describe in detail the approach which has been briefly introduced here. Following on from this first introductory chapter, the second chapter provides essential theoretical and technological background for this work. To begin with, the physics and physiology behind our perception of colour are described before introducing colorimetry and colour science. Key concepts such as the appearance, measurement, description and reproduction of colour are covered. Finally, colour display technology is introduced, paying particular attention to the sort of display devices that are in everyday use in colour computer systems.

The third chapter looks at colour in design. The basis for this was a series of interviews held with textile garment designers selected from a number of different sites in the UK. Detailed reports for each interview are given in Appendices A-F. Although the overall design process was covered, greater attention was paid to the role of colour in their work, where it was communicated and at what stages colour fidelity was a concern. Since the majority of the designers questioned already used computer aided design systems, it also provided an opportunity to study the extent to which their existing technology supported (or hindered) their work.

Chapter four examines some of the current approaches to the problems surrounding colour in computer-based design systems highlighted in the preceding chapter, specifically looking at colour fidelity and communication (those being found to be the chief areas of concern to those designers that were interviewed). In looking at colour fidelity, various colour management systems are introduced and compared. A number of facets of colour communication are covered including standards and formats for exchanging colour imagery, systems for representing colour spaces on computer displays and the interrelation of different notation systems. Following this, the chapter looks at what solutions are currently available on the market that try to address the designers' requirements. Finally, the limitations to achieving high colour fidelity on computer displays are addressed.

Chapter five details the proposed solution to the requirements for accurate colour reproduction and improved colour communication. After setting out the aims and justification for such a solution (prompted by the requirements of the designer interviews covered in the third chapter), a detailed description of the approach is given. To begin with, it is advocated that "what you see is what you get" should be an important goal and that device characterisation and colour appearance modelling are essential components necessary to achieve this aim. For successful communication, the representation and content of the information describing a colour are important and a suitable format is proposed which is appropriate to the designers' needs. In addition, a method for supporting colour selection via a number of colour order systems is given together with a means of interrelating them to further facilitate communication. Finally, a set of recommendations are given concerning the representation of colour within the system's user interface. Usability concerns aside, proper use of colour on the display is essential in order to prevent colours being misperceived due to incorrect presentation.

Following on from this, the sixth chapter describes the implementation details of an actual computer-based system, *ColourTalk*, which has been created and subsequently used by some of the designers that were originally interviewed earlier for a real design task. The chapter begins by detailing a method for monitor calibration and characterisation which is essential for obtaining precise, repeatable colours on the display. Next, the mathematical mappings which are used to model and interrelate the various colour notation systems are explained together with a report of how their performance was evaluated. This is followed by a description of the initial prototype system that was developed and includes the hardware used and the system's main functions. The final system, which was further refined from the prototype as a result of lessons learned, is discussed. Finally, the system's evaluation in terms of both its colour fidelity and usefulness for real tasks is given.

In conclusion, the seventh chapter summarises the results and findings of the preceding chapters. Also covered is a review of the effectiveness and limitations of the approach that has been proposed. Finally, possible future directions are suggested both to extend the scope of this work and also as to how the results might be incorporated into future CAD systems.

1.4 FURTHER READING

Although colour has long been the subject of study (since the earliest recorded history in fact), it is only relatively recently that a deeper understanding of the subject has begun to develop. Also, the field of colour imaging technology is rapidly evolving with new imaging devices being produced on a regular basis. As previously stated, the following chapter does introduce the topics of colour science and technology. To supplement this, a list of references is now given which provide a greater depth of coverage. Other introductory material includes [Cumm90a, Bill81a]. For further background on colour science, see [Hunt92a, Hunt87a, Judd75b, McDo87a, McLa86a, Witt82a, Hunt87b]. A number of sources of information regarding the use of colour in computer systems are available, including [Fole84a, Trav91a, Jack94a]. Finally, more information on colour imaging devices can be found in [Durb88a, Sher88a, Spro83a].

Chapter Two

Colour Science and Technology

CHAPTER TWO: COLOUR SCIENCE AND TECHNOLOGY

2.1 INTRODUCTION

Evidence of the awareness of colour has been seen in the prehistoric cave paintings of 20,000 years ago [Tonn93a] and has been studied extensively throughout the intervening millenia. By 2,000 BC, the Chinese had developed a "five-colour" concept† which was used to signify the rank of officers and had even identified the phenomenon of colour blindness [Dong88a]. The early Greek philosophers made a number of interesting speculations; Empedocles (492-431 BC) described the eye as being a torch emitting light while Plato (427-347) thought that "God only has the knowledge and also the power" to see "how and by what mixtures the colours are made" [MacA70a]. It was not until Aristotle realised that colour "is not visible except with the help of light" and "seeing is due to an effect on or change of what has the perceptive quality" that any real understanding of colour developed [MacA70a]. Aristotle also developed an ordering of colour according to the growth and ripening of living things (e.g. the ripening of fruit and the growth of animals) [Dere91a]. During the renaissance period, Leonardo da Vinci (1470-1530) proposed six primary hues ("white is the first amongst the simple, and yellow is second, green is third, blue is fourth, red is fifth, and black is the sixth") [Vinc56a]. Later, the Swede Sigfrid Aronus Forsius wrote a monograph [Fors52a] in which he presented a colour circle to systematically describe colour. However, it was not until 1666 when Sir Isaac Newton (more of whom shortly) split white light that the foundations for our present day understanding of colour were truly laid.

In this second chapter, the subject of colour science and technology is introduced, beginning with the physics of colour and the physiology of the visual system. The keystone of colour science, colorimetry, is described together with its applications. After briefly covering colour appearance, various schemes for colour notation are reviewed before finally looking at some of the technology currently available for reproducing colour.

† However, they did not include green as one of these primary colours, instead regarding this as an intermediate colour.

2.2 THE NATURE OF COLOUR

Introduction

The phenomenon of colour is a result of the physical interaction of light source, object being illuminated and the observer. In addition, our own perception of colour is influenced by certain physiological and psychological factors. Each of these components are examined in the section that follows.

2.2.1 The Physics of Colour

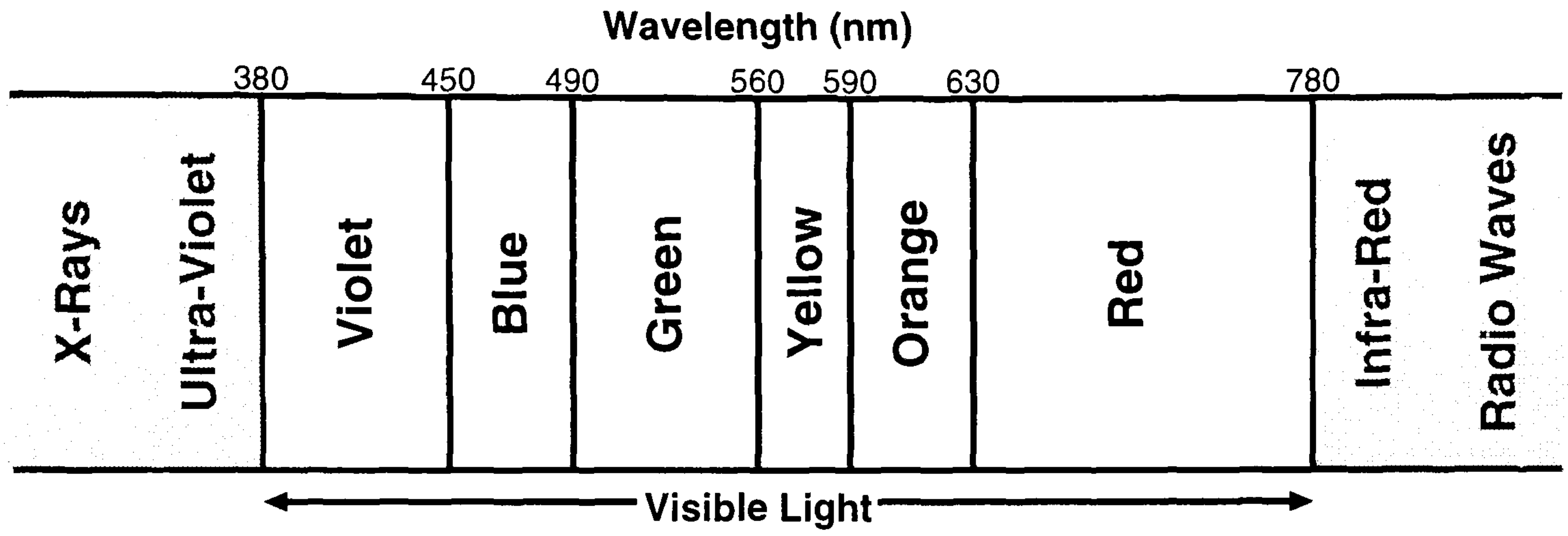
> "Nature, and Nature's laws lay hid in night: God said, *Let Newton be!* and all was light."
> — *Alexander Pope (1688-1744), Epitaph for Sir Isaac Newton*

In 1666, revolutionary experiments conducted by Isaac Newton at Trinity College, Cambridge, revealed that white light was in fact composed of a mixture of all the colours of what he named the *spectrum*. His experiment was carried out in a darkened room in which a small hole had been made to let in direct rays of sunlight, somewhat like a giant pin-hole camera. By placing a glass prism close to the hole, Newton observed that the incident light was spread out in a fan-like pattern of different colours. Next, a card with a thin slit was used to block out all but a narrow beam of coloured light from the prism. Another prism was then placed in the path of this light and it was seen that the light could not be further divided and remained the same colour. From these observations, Newton had effectively demonstrated the non-homogeneity of daylight. He also concluded that the colours he had seen (red, orange, yellow, green, blue, indigo† and violet) were fundamental components of light. Arguably, though, the most important contribution made was that, as a consequence of Newton's work, colour was treated as a subject of modern scientific study.

Following the work of James Clerk Maxwell in 1860, we now know that visible light is actually a form of electromagnetic radiation which also comprises x-rays, radio waves, ultraviolet and infra-red light (see Figure 2.1). Light is usually described by its *wavelength*, typically using the nanometer or nm scale, where $1\text{nm} = 1 \times 10^{-9}\text{m}$. The eye (discussed later in §2.2.2) is sensitive to only a relatively narrow band of the spectrum, thus limiting the visible range to between approximately 380 (violet) and 780nm (red). The

† The rather surprising inclusion of indigo amongst these (there appearing only a gradual transition between blue and violet) is thought to be because Newton believed that the colours should be ordered in scale of tones akin to that used in music [McLa85a].

Figure 2.1: The Visible Part of the Spectrum



light that is produced by a light source can be described in terms of the relative power (or energy) emitted at each wavelength. It is usual to normalise such data so that the power at wavelength 560nm has an arbitrary value of 100 (hence values at other wavelengths will be scaled relative to this). If this is plotted as a function of wavelength, the light source's *spectral power distribution* (or SPD) can be seen. An example of such a curve can be seen in Figure 2.2 which shows the relative spectral power between 300-900nm of typical daylight. (Obviously, the precise nature of real daylight will vary according to such factors as atmospheric conditions, latitude and time.)

Another important source of light in physics is the *black body* or *Planckian* radiator. Such objects have the property that their power distribution, and hence their colour, depends only on their temperature and not their composition. Upon heating, they glow like metals beginning with a dull red and becoming progressively brighter and whiter. Real black bodies are hollow heated chambers, although tungsten filaments (such as those commonly used in incandescent lighting) behave as good approximations. The temperature of a black body is known as its *colour temperature* and is measured in degrees absolute, or Kelvin (K). Figure 2.3 illustrates the effect of temperature on SPD for Planckian radiators. The term colour temperature is also applied to some incandescent light sources (e.g. tungsten filament lamps). Fluorescent tubes and combinations of incandescent lamps and filters whose light does not have a *chromaticity* (or colour) exactly the same as that of any black body radiator are described in terms of their *correlated colour temperature*, i.e. the temperature of a black body radiator whose colour is nearest to that of the source. An example of correlated colour temperatures for some everyday light sources [Hunt92a] is given in Table 2.1 .

Figure 2.2: Spectral Power Distribution Curve for Typical Daylight

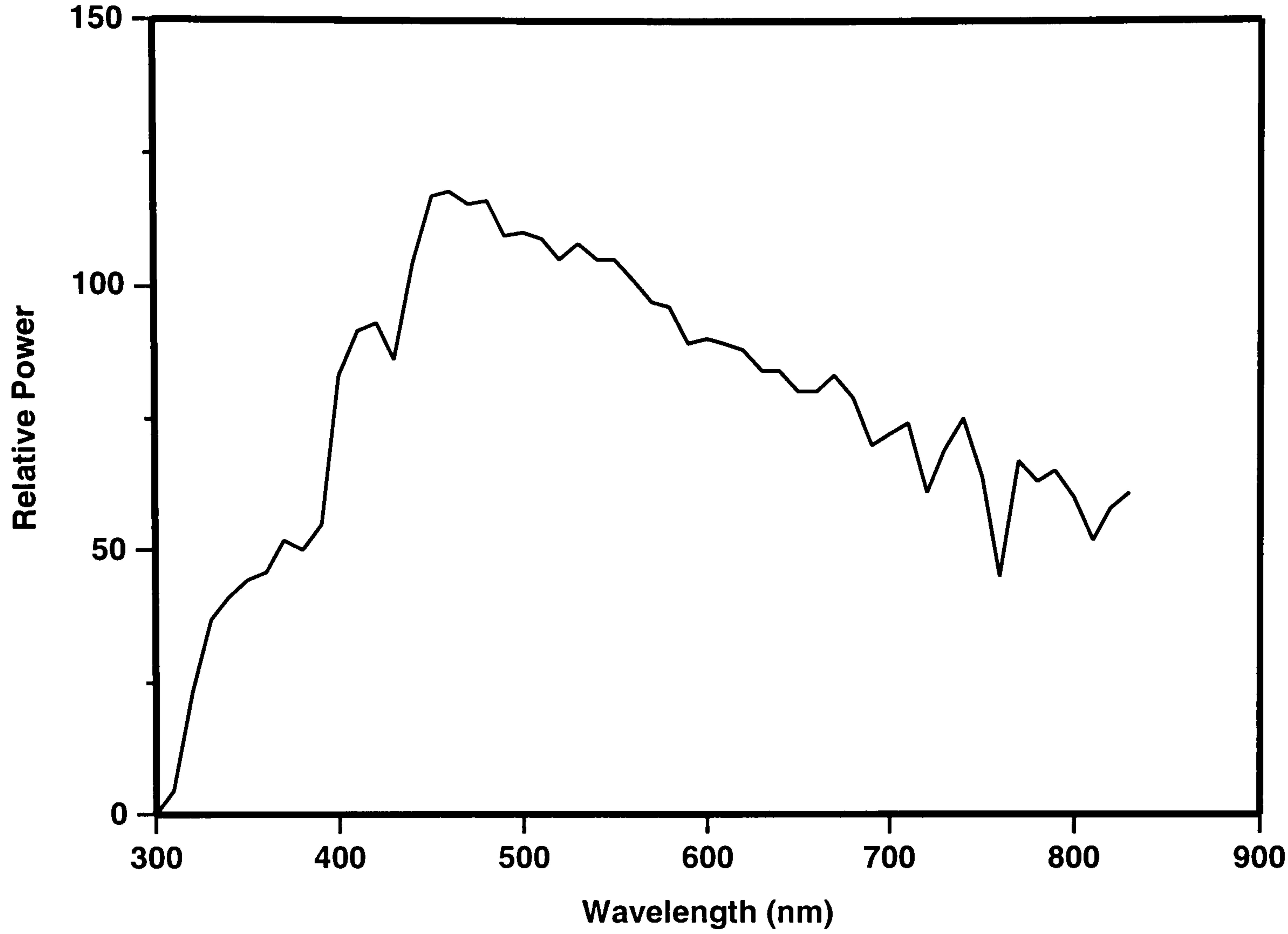
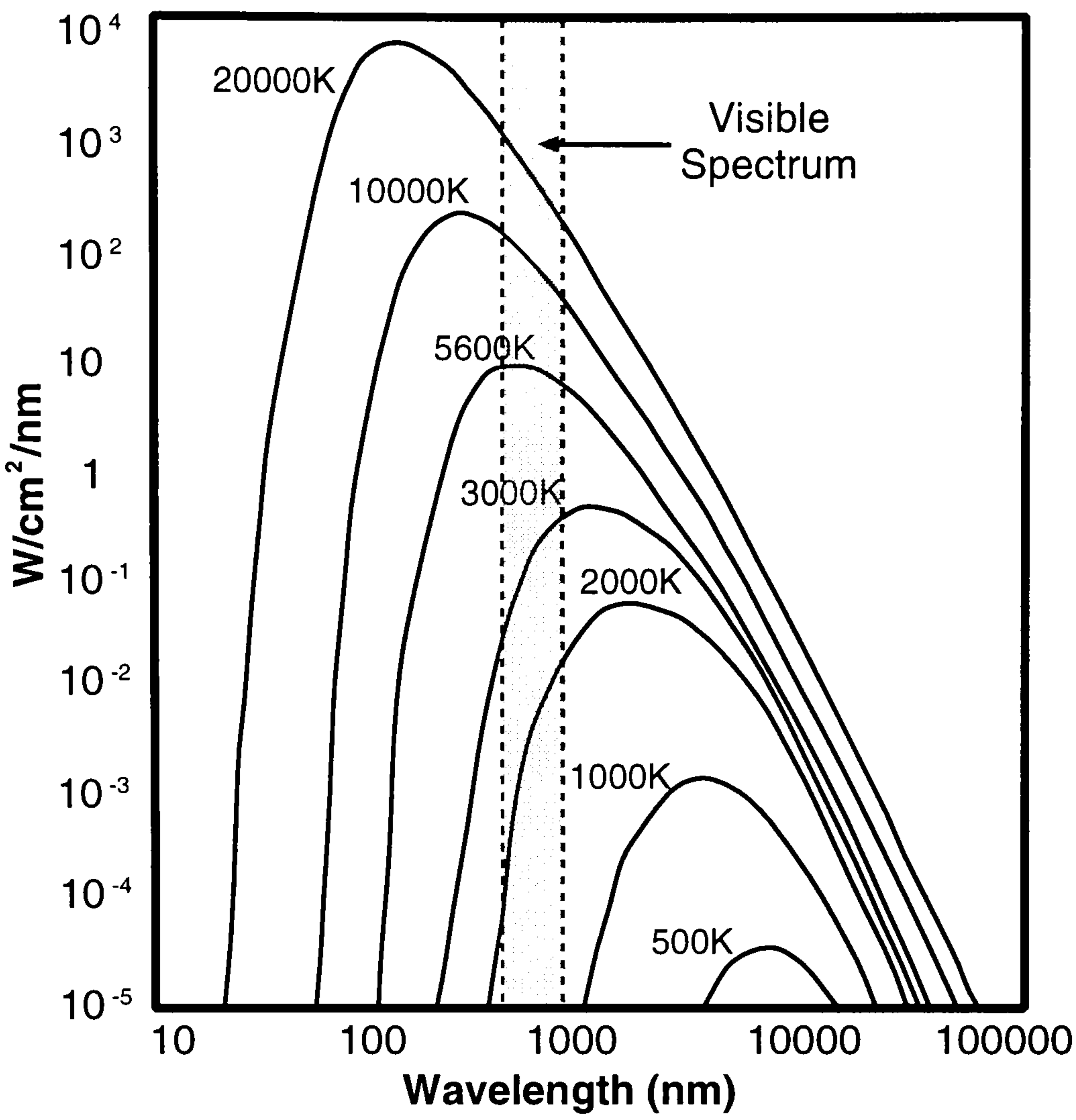


Table 2.1: Correlated Colour Temperatures for Everyday Light Sources

Source	K
North sky light	7500
Average daylight	6500
Fluorescent lamps	6500
Xenon flash	6000
Sunlight plus skylight	5500
Fluorescent lamps (cool white)	4200
Projection tungsten lamps	3200
Fluorescent lamps (warm white)	3000
Tungsten lamps (domestic, 100W)	2800
Tungsten lamps (domestic, 40W)	2700
Sunlight at sunset	2000
Candle light	1900

As can be seen, daylight is a very variable source and even the light produced by artificial sources such as a heated tungsten filament change considerably due to such factors as age, applied voltage and dimensions. Everyday experience tells us that object colours do not appear the same when their

Figure 2.3: Spectral Power Distribution of Planckian Radiators at Different Temperatures

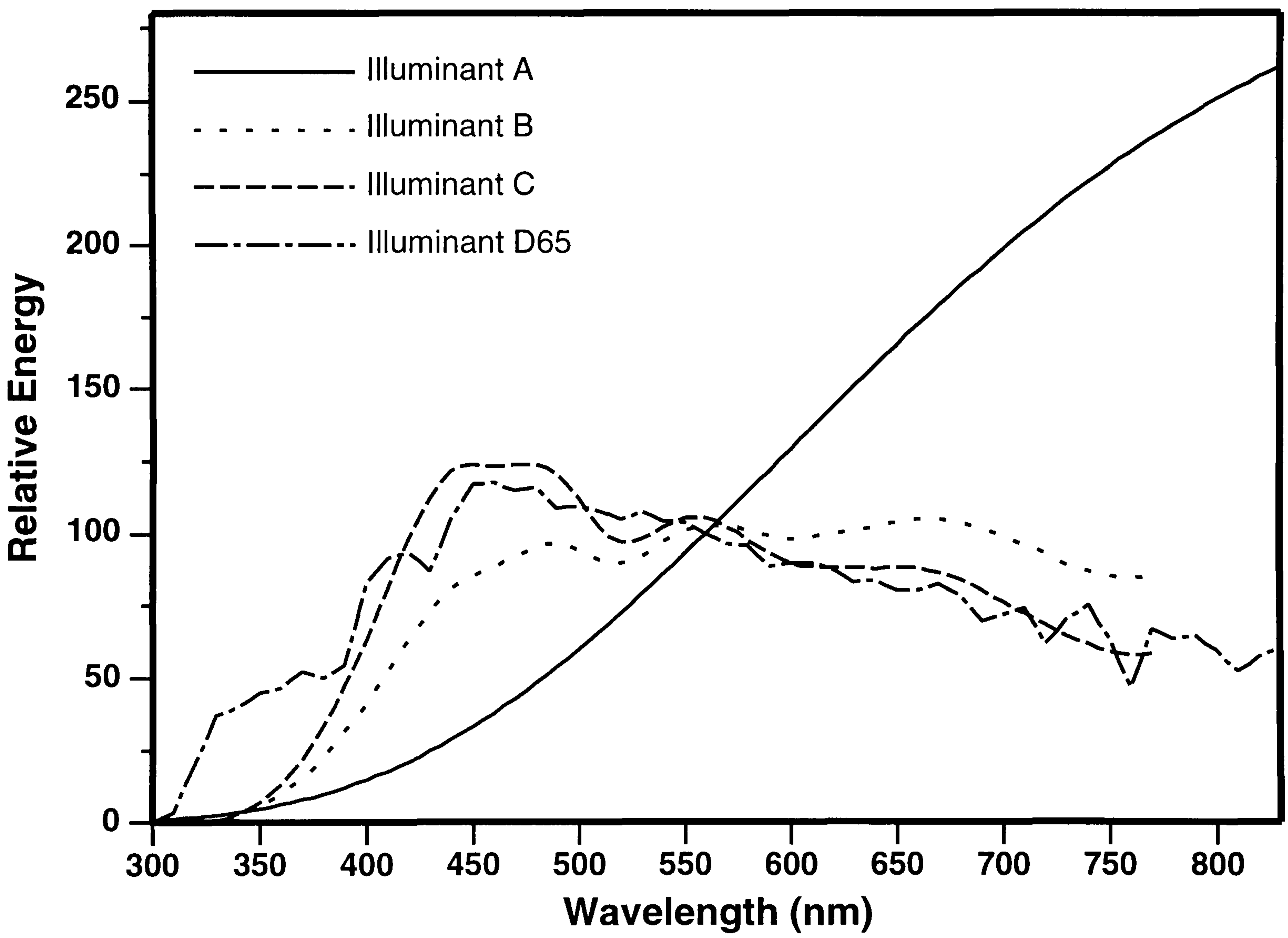


illumination changes. Furthermore, this makes the accurate and repeatable measurement or comparison of colour particularly troublesome. Hence, it is desirable to precisely control and define the energy of the light source. In 1931, the international committee on illumination, the CIE (Commission Internationale de l'Éclairage), proposed a series of standard illuminants: A, B and C, later supplemented by illuminant D_{65} in 1963 [CIE85a] (see Figure 2.4). Formally, all sources of light may be categorised as follows:-

- *Light source:* a physically realisable producer of radiant power.
- *Illuminant:* a light which is defined by a spectral power distribution which may or may not actually exist in physical form. If such a physical form is available, it is known as a *standard source.*

CIE illuminants A, B and C can be realised by physical sources and these were, in turn, chosen to be representative of other common physical sources. Illuminant A was devised to be representative of light produced from a gas-filled tungsten filament lamp. (It is actually defined to be an illuminant having the same relative spectral power distribution as a Planckian radiator at a temperature of 2856K.) Illuminants B and C were intended to simulate outdoor lighting (direct noon sunlight (4900K) and average daylight (6800K) respectively). Both B and C are defined only in terms of their relative spectral power distributions. CIE illuminant D_{65}, having an approximate correlated colour temperature of about 6504K, is one of a series of D illuminants representing daylight conditions of different colour temperatures designated D_{50}, D_{55}, etc. for correlated colour temperatures of approximately 5000K, 5500K, etc. D_{65} represents average indoor daylight. Unfortunately, no CIE sources exist that realise the D series of illuminants and therefore any physically simulated source can only approximate the chromaticity rather than the spectrum of the theoretical standard.

Figure 2.4: CIE Illumimants



When light strikes an object, a number of different physical effects can occur which modify the colour of that light. These are:-

Transmission and Reflection

Incident light passes through (i.e. is *transmitted* through) a transparent material. For colourless materials, all the light is transmitted with the exception of that which is *reflected* from the two surfaces. Reflection occurs whenever there is a change in the *refractive index* of media. This index is a measure of the relative slowing down of light compared with its speed in air. Typically, at each boundary that is crossed, light changes speed and consequently there is usually some portion of it that is reflected. Additionally, there may be a change in direction (called *refraction*) which is wavelength-dependent and is the same phenomenon witnessed by Newton in his work with prisms.

Absorption

During transmission, light passing through an object may be absorbed. If part of this is absorbed, the light may appear coloured. If all the light is absorbed, the material is said to be *opaque*. Similarly, for reflection, if all the light is absorbed by the material it appears black.

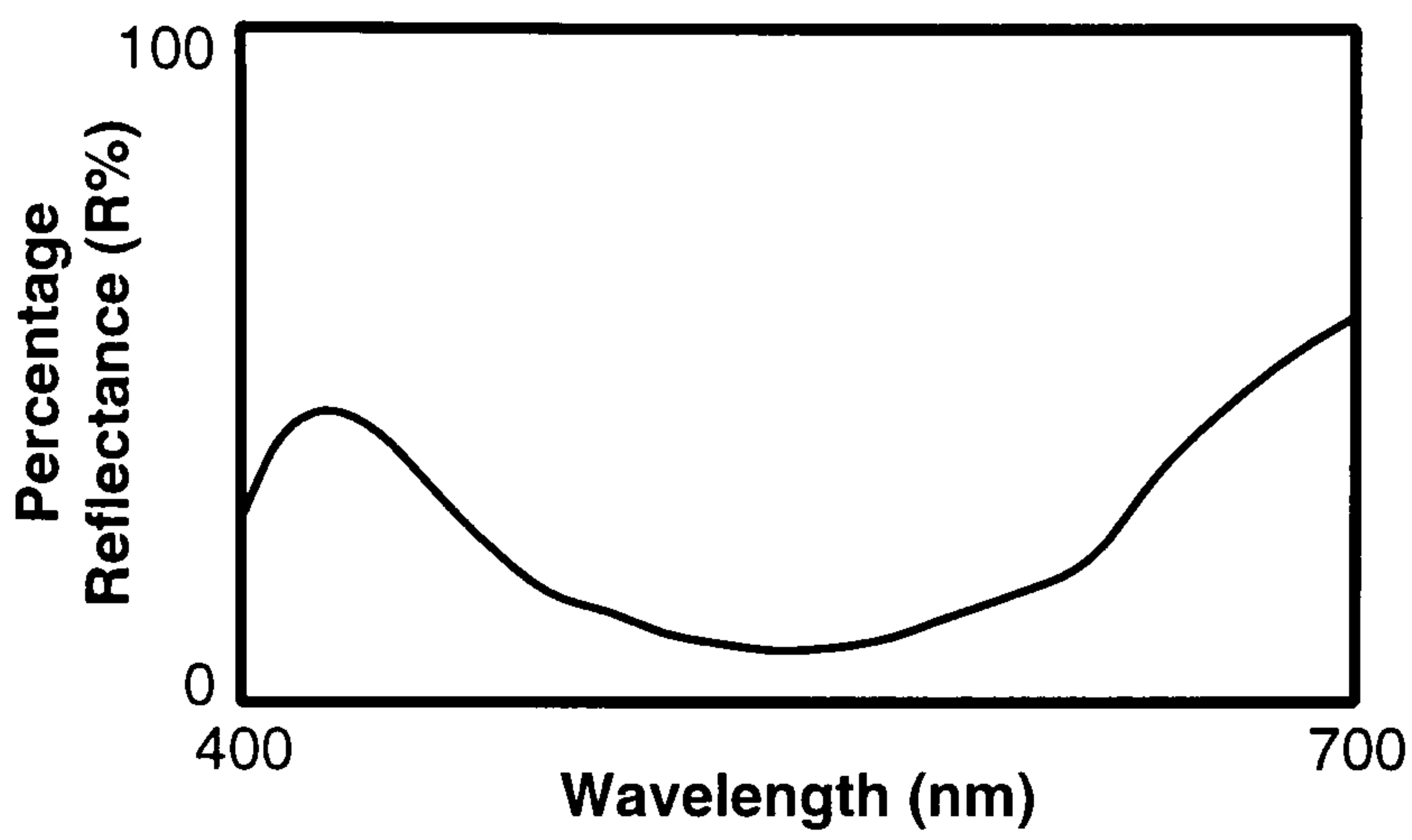
Scattering

When it interacts with matter, light may be scattered. Part of the light is absorbed and re-emitted at the same wavelength as before, and part travels around in many different directions. The blue colour of the sky is due to scattering of light by air molecules.

Another related phenomenon is *gloss* which is a result of *specular* (mirror-like) reflection of light from smooth surfaces. As the surface becomes rougher, gloss diminishes. A fully matte (non-glossy) surface acts as a *diffuse* reflector.

Previously, it was seen how spectral power distribution curves could be used to describe light sources. The effect of light on an opaque object can be described in terms of a *reflectance curve*. Such a curve represents for each wavelength the proportion of light that is reflected from an object relative to that reflected by a white standard. Alternatively, for transparent samples, *spectral transmittance* curves record the fraction of light transmitted through the material at each wavelength relative to some suitable standard, usually air. In Figure 2.5, which shows an example of a reflectance curve for an opaque surface sample, it can be seen that the purple colour of the object is actually the result of it reflecting red and blue light and absorbing green light. If only red light is shone on this object, only red light will be reflected and it will

Figure 2.5: Example Spectral Reflectance Curve for a Purple Colour



appear red. Thus, it can be seen that an object's apparent colour depends upon both its spectral reflectance (or transmittance) and the SPD of the light source used to illuminate it. A third factor, the observer, also plays a key role in the phenomena of colour.

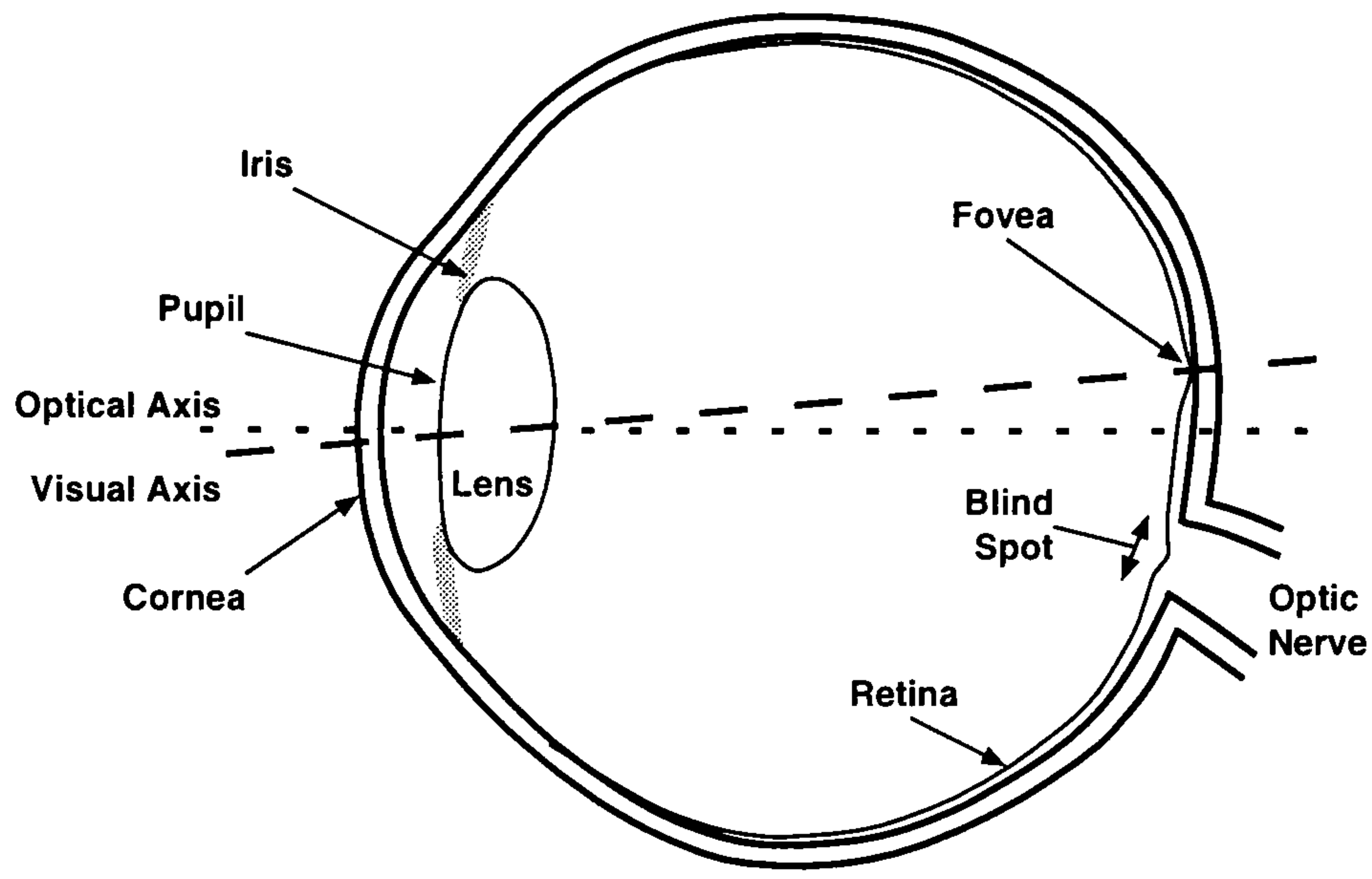
2.2.2 The Visual System

The human visual system is perhaps the most important detector of colour (at least, as far as we are concerned) whose complexities are only just beginning to be unravelled. It has been estimated that we are capable of distinguishing between approximately *ten million* different colours [Judd75b], however the number of colours we are capable of accurately remembering is considerably less than this. The visual system consists of the eye, the optic nerve and the brain. Hence, our perception of colour is essentially a process involving physics, physiology and psychology.

The Eye

Light enters the eye, as illustrated in Figure 2.6, passes through the *iris* and is focussed on the *retina*. Focusing is achieved through a combination of the *cornea* and *lens*. The cornea is of fixed curvature and accounts for most of the eye's optical power. The lens is capable of altering its shape in order to focus light from both close and distant objects. Together, the cornea and iris produce a small inverted image on the light-sensitive surface of the retina. The amount of light reaching the retina is controlled to some degree by the iris. This consists of a coloured annulus comprising a central hole, the *pupil*, through which light

Figure 2.6: The Eye



passes. By changing its shape, the iris can vary the size of the pupil to compensate for a range of different illumination levels.

Although the retina covers most of the interior of the eye, its sensitivity is concentrated around 40° of the visual axis, with the sharpest vision being experienced at the *fovea*, itself covering a field of about 5°. Outside this 40° area, peripheral vision is largely monochrome and mainly used for sensing movement. Within this area, the eye is able to see both detail and colour except for one point where the optic nerve links the retina to the brain which is known as the *blind spot*. Within about 1.5° of the fovea (known as the *foveola*), the retina is composed of *cone* receptors. Outside of this area, there are both *rod* and cone receptors, however beyond about 40° from the visual axis, the retina is comprised mainly of rods. (The cone and rod receptors are so named because of their shape.) Rods function to provide monochromatic vision under reduced illumination level conditions. This is also know as *scotopic* vision. Cones provide colour vision at "normal" levels of illumination (several cd/m^2 or more), known as *photopic* vision. The rods and cones are connected via a complex network of cells to the nerve fibres leaving the eye at the blind spot.

Both rods and cones contain photosensitive pigment (which, in the case of the rods, is known as *rhodopsin*), however they do not possess the same spectral sensitivity to light. Furthermore, there are actually three different types of cones, named ρ, β and γ, each of which have different spectral responses. Illustrated in Figure 2.7a is the relative spectral sensitivity for each type of rod and cone (rod response is represented by a broken curve) obtained by microspectrophotometric measurement of the absorption spectra of photoreceptors [Dart83a]. From this, it can be seen that the peak sensitivities of ρ cones are at around 560nm (the red part of the spectrum), γ at 530nm (close to green) and β at 420nm (blue). It should be noted that there is a considerable overlap in cone response — this is particularly evident when log sensitivity is plotted as in Figure 2.7b — so, for example, the ρ cones are also sensitive to green light. (In vision science, the β, γ and ρ cones are conventionally named S, M and L respectively according to their sensitivity to the short, medium and long wavelength part of the spectrum.) The distribution of the different types of cone throughout the retina is apparently random, however there are far fewer β cones than either ρ or γ (the ratio of $\rho : \gamma : \beta$ is approximately 40:20:1 [Cice89a, Vima89a]). One possible explanation for this is the eye's inability to sharply focus on the three regions of the spectrum at once due to optical chromatic aberration.† When the eye focuses on light of around 545nm (i.e. between the peaks of the γ and ρ response curves) the light detected by the β cones will be considerably fuzzier and hence having many β cones wound not be advantageous. Because our colour vision is dependent upon three classes of receptor, it is said to be *trichromatic*.

The Visual Signal

Light striking the retina's receptors causes excitation of molecules in their photosensitive pigment which in turn produces a small electric voltage. This is transmitted along a nerve fibre into the brain as a pulse-width modulated signal. All information is carried in the signal's frequency and not in its amplitude. A shorter pulse width (i.e. a higher rate of pulses) indicates a stronger signal. Rather than having separate signals for each receptor type (rod and cones), it is thought that the visual system employs a more complex encoding scheme. Physiological studies [Derr84] have led to the model of colour vision depicted in Figure 2.8. In this diagram, it can be seen that the ρ, γ and β cone receptors are connected to nerve cells or *neurons*. Three classes of neurons sum their inputs from the receptors to produce a luminance signal, $\rho + \gamma$, and two colour difference signals are formed by differencing signal receptor outputs $\rho - \gamma$ and $\beta - (\rho + \gamma)$ as

† Chromatic aberration, due to light passing through a lens being refracted by differing amounts and hence being focussed at differing points according to its wavelength, is also responsible in part for the perceived depth effect known as *colour pseudo-stereopsis* or *chromostereopsis*. One example of this is when saturated blue and red text is viewed on a black background resulting in an apparent difference in relative depth of each colour.

Figure 2.7a: Spectral Sensitivity of the Eye

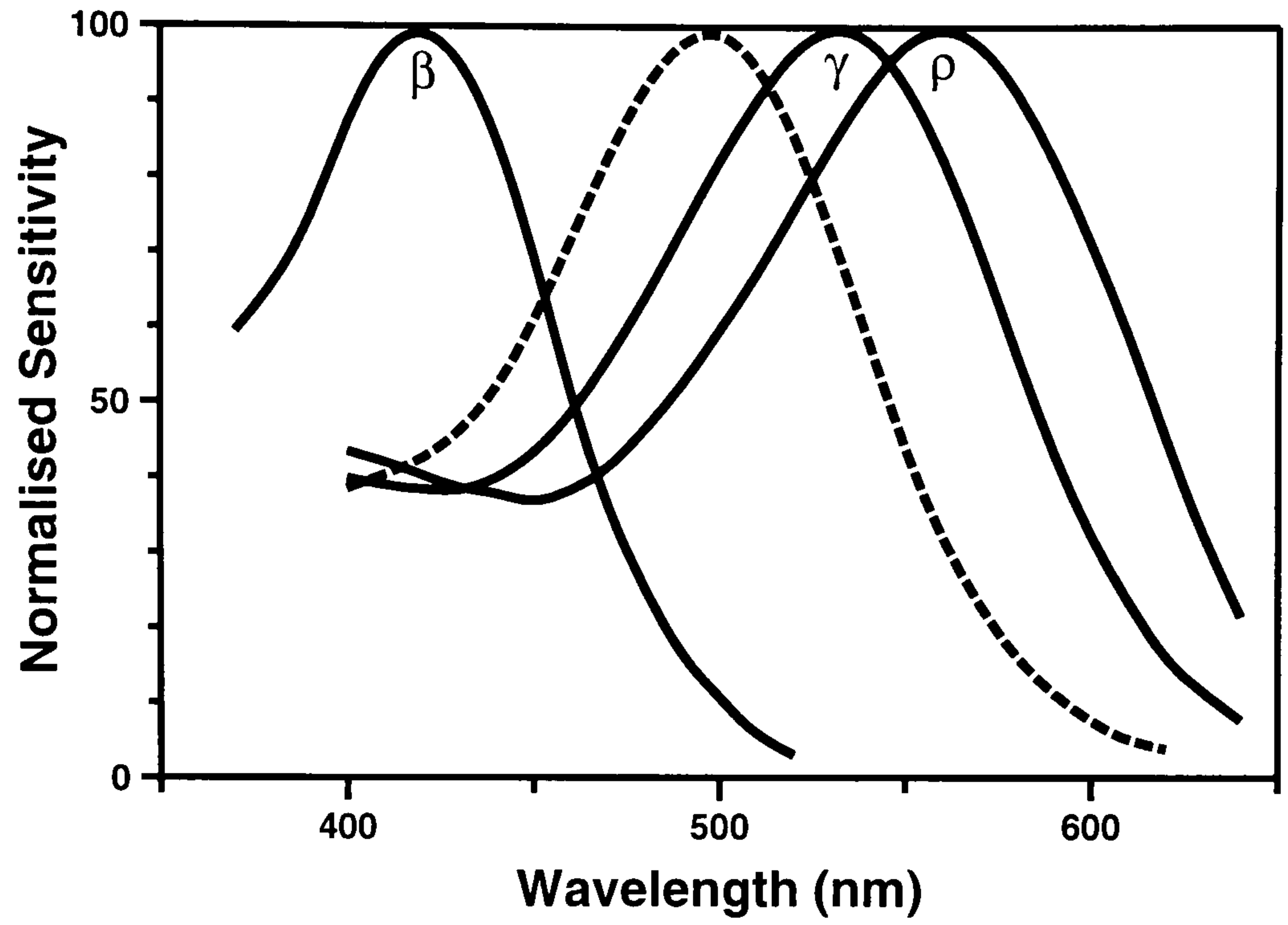
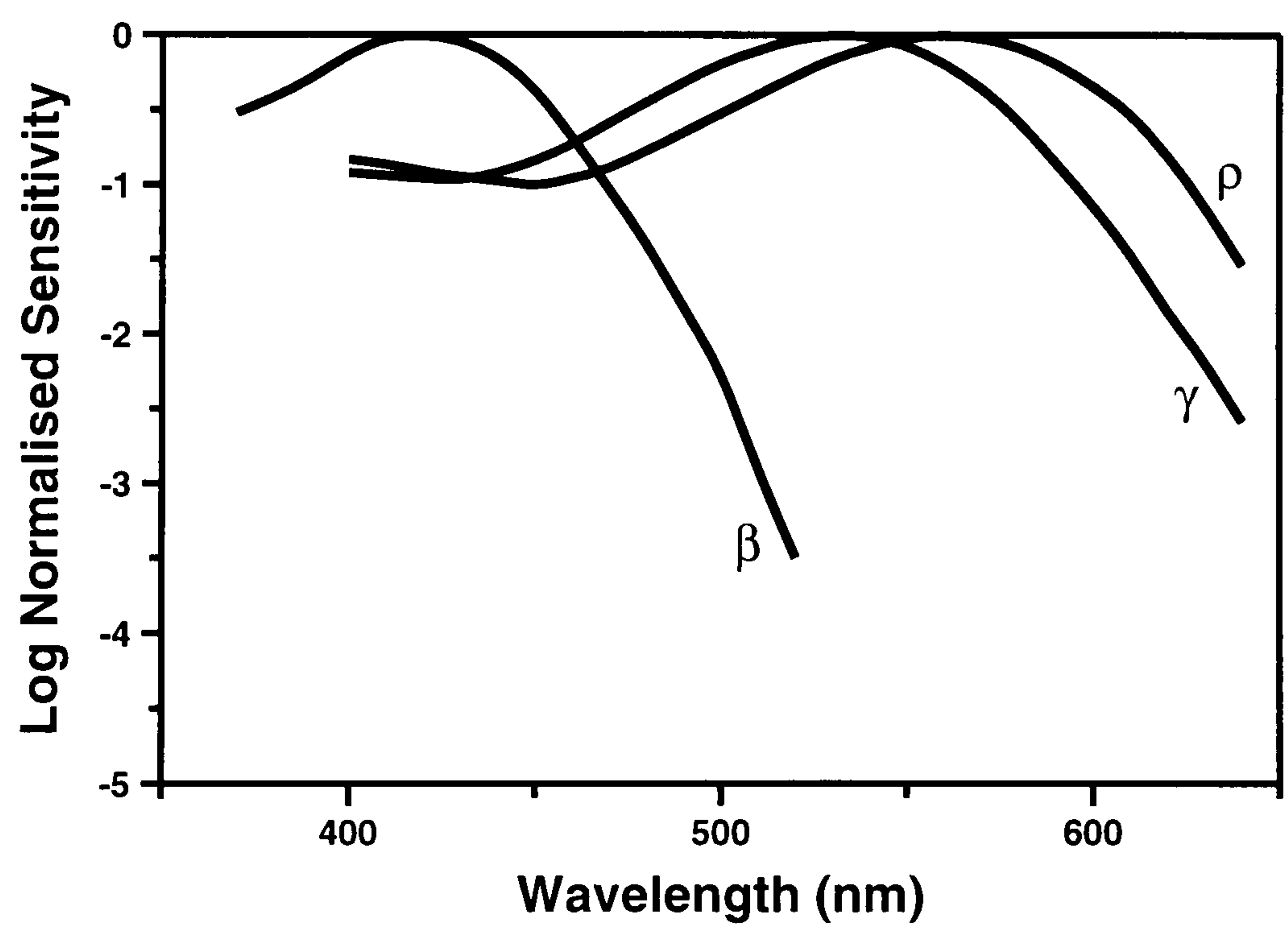
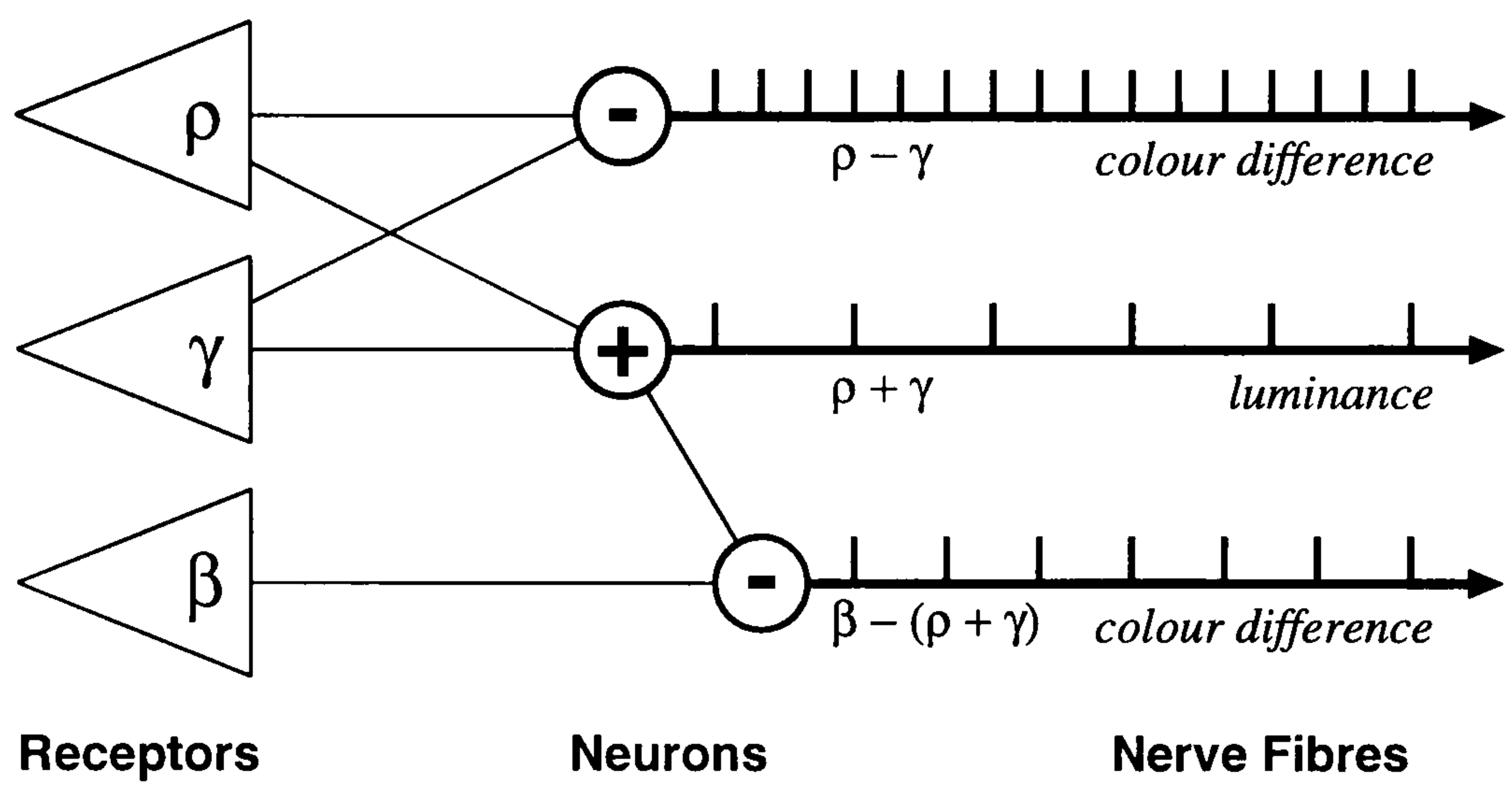


Figure 2.7b: Log Sensitivity of the Three Cone Types



illustrated. Note that the short wavelength β cones are thought not to contribute to luminance perception. For this reason, it is often difficult to discern blue text on a black background or yellow text set against a white background because the luminance contrast is so low. At the final stage of colour vision, the signals are interpreted by the visual cortex, the region of the brain responsible for visual perception. The brain also accounts for a number of colour appearance phenomena which include colour constancy and simultaneous contrast (both introduced in §2.2.3).

Figure 2.8: Hypothetical Representation of Visual System Connectivity



Colour Deficiency

Finally, before leaving the subject of colour vision, it should be realised that approximately eight percent of the male population and 0.4 percent of the female population suffer from "colour blindness" of one sort or another. Such colour blind or, more properly, *colour defective* people typically have a reduced ability to differentiate between certain colours. Colour deficiency is acquired either genetically or as a result of pathology; the inherited cause affects mostly males. It has been categorised [Hunt92a] and these classifications are summarised as follows:-

Anomalous Trichromacy

- *Protanomaly* — the reduced ability to discern between reddish and greenish components of colours with reddish colours appearing appreciably dimmer than normal. Thought to be due to the ρ cones' spectral sensitivity being shifted towards that of the γ cones.
- *Deuteranomaly* — the reduced ability to discern between reddish and greenish components of colours without any colours appearing dimmer. Thought to be due to the shifting of γ cone sensitivity towards that of the normal ρ cones.

- *Tritanomaly* — the reduced ability to discern between yellowish and bluish colour content. Believed to arise as a result of a shift in the spectral sensitivity of the β cones towards that of normal γ cones.

Dichromacy

- *Protanopia* — the extreme reduction in the ability to discern between reddish and bluish colour content together with reddish colours appearing dimmer than normal; due to the absence of ρ cones which are probably replaced by γ cones.
- *Deuteranopia* — the extreme reduction in the ability to discern between reddish and bluish colour content together without any colours appearing noticeably dimmer than normal. Thought due to γ cones being missing which are probably replaced by ρ cones. (The ρ and γ spectral sensitivity curves are similar for shorter wavelengths — see Figure 2.7b — and hence result in similar brightness.)
- *Tritanopia* — the extreme reduction in the ability to discern between bluish and yellowish colour content. This results from the absence of β cones, although the lack of contribution of these cones to the achromatic signal results in a roughly normal brightness response to colours.

Monochromacy

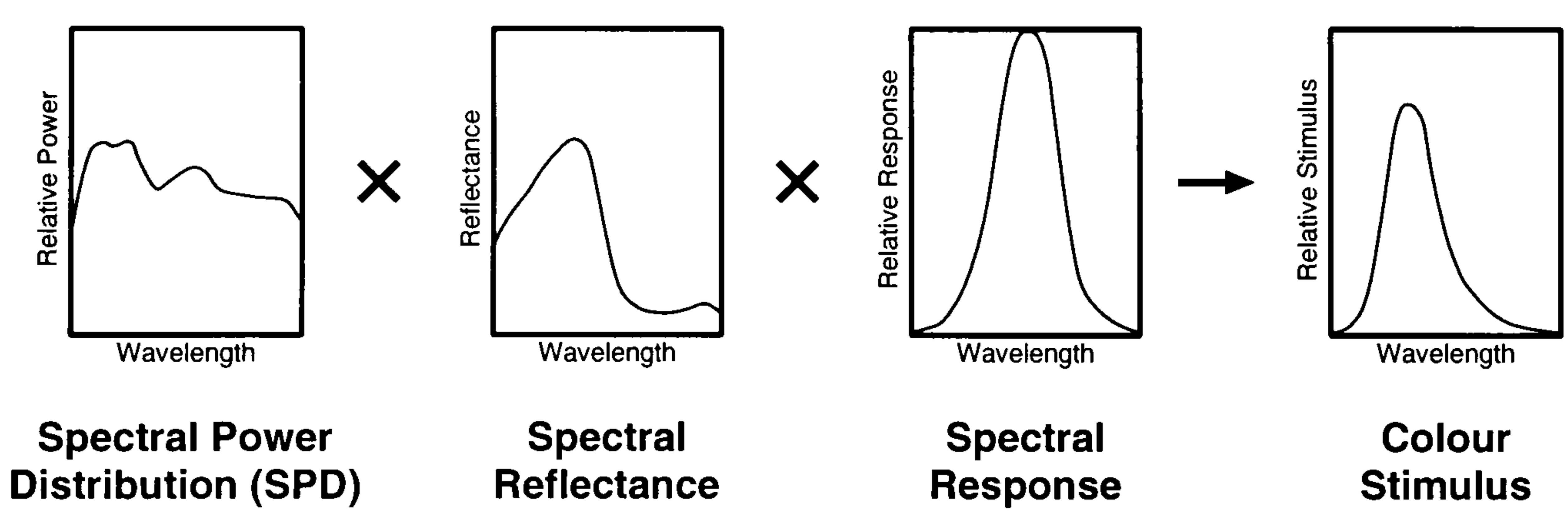
- *Rod Monochromatism* — the inability to discriminate colour or brightness as a result of having no cones. In effect, this is somewhat similar to scotopic vision.
- *Cone Monochromatism* — the inability to discriminate colour but with reasonably normal brightness discrimination. This is due to both β and γ cones being absent (and hence is a combination of deuteranopia and tritanopia). Another possible cause is the lack of a colour difference signal.

Colour deficiency is usually identified using a series of colour confusion (or pseudo-isochromatic) test charts such as those developed by Ishihara and others [Ishi85a, Poko79a].

2.2.3 Colour Appearance and Related Phenomena

The final stage of our perception of colour takes place in the brain however the visual signals reaching it are fundamentally dependent upon three things. Firstly, the light source providing the illumination which can be described in terms of its SPD. Secondly, the object is being lit by the light source which reflects light according to the material's surface reflectance curve. Finally, the observer's retina which detects light according to its own spectral sensitivity. Changing either of these three results in a different perceived colour (or indeed a different instrumentally measured colour) as illustrated in Figure 2.9. The effect of switching between different light sources such as daylight and tungsten can be quite dramatic which is why when one is buying colour-critical goods from a shop it is often prudent to hold them up to a window to examine their appearance under natural lighting. Another variable factor in illumination is the intensity of the light source. Changing an object's material typically changes its physical properties and hence the way in which light is reflected from its surfaces. Also, observers themselves may not see colours in precisely the same way due either to small differences in their eyes' spectral response characteristics or (more dramatically) as a result of colour deficiency.

Figure 2.9: Components of a Colour Stimulus



The human visual system can, to a large extent, compensate for changes in both lighting level and colour. This is the result of a process known as *adaptation* which also occurs with other sensory stimuli. Adaptation may be further broken down into *luminance adaptation*, which compensates for luminance (or brightness) differences, and *chromatic adaptation*, which compensates for differences in white point or illuminant colour. Consequently, through adaptation, colours tend to look approximately the same under a variety of different viewing conditions. This effect is called *colour constancy* and plays an important role in the perception of colour.

Another related phenomenon is *metamerism* which can be defined as being when two colours (forming a *metameric pair*) match under one set of conditions but fail to match under another. Matching in this sense means yielding a similar visual colour stimulus, as seen previously in Figure 2.9. Human colour vision is trichromatic in nature (i.e. it is dependent upon the stimulation of the three cone types which themselves integrate light over a range of different wavelengths) and not based on a precise wavelength by wavelength response. Hence, there are an infinite number of combinations of different spectral values for light source SPD, object reflectance and observer response which ultimately yield the same colour stimulus. Four different types of metamerism have been identified [Rigg87a] and these are:-

(a) Illuminant Metamerism

(b) Observer Metamerism

(c) Field Size Metamerism

(d) Geometric Metamerism

By far the most common type of metamerism is that caused by different light sources (a) and arises through each having a different SPD. Observer metamerism (b) is less obviously seen and is due to differences in the spectral response of observers (which might also be as a result of colour deficient vision). The field size (c) of an object (measured as the angle subtended at the eye) can mean that pairs of objects viewed at a distance may match whilst they fail to match when viewed close up. Again this effect is thought to be due to differences in the spectral response. Geometric metamerism (d) can occur whenever there is a change in viewing geometry. Metallic paints and certain textiles are particularly prone to this kind of effect when their angle of illumination is altered. This effect can be regarded as affecting the spectral reflectance of the object being viewed. Practically, metamerism can occur in varying degrees however it is usually the goal of industry to minimise its effects.

Colour perception is dependent upon adaptation which in turn depends on all the stimuli present in the visual field. This gives rise to an effect known as *simultaneous colour contrast* whereby colours appear different according to which colours surround them or are adjacent to them. Figure 2.10 shows an example of this effect; the same patch surrounded by a light grey border (left) appears darker than the same patch surrounded by a dark grey border (right). As well as lightness, simultaneous contrast can also affect the perceived hue of a colour (see Colour Plate 3), however despite much research into this area, this phenomenon is not well understood.

Figure 2.10: Demonstration of Simultaneous Colour Contrast

2.3 BASIC COLORIMETRY

Physical colour stimuli can be described by their spectral power distributions, formed from the SPD of an illuminant and modified by the spectral reflectance factor or spectral transmittance factor of an object (§2.2.1). Unfortunately, colour perception is a subjective phenomenon dependent upon both viewing condition and observer and as such is difficult to quantify. One way of overcoming this adopted by the CIE in 1931 is to standardise on both the light source and observer. This section introduces the CIE system and its application to the measurement of colour, otherwise known as *colorimetry*. Much of all conventional colour measurement is based on the CIE system of colorimetry. The basis for the CIE system dates back to the work of Grassmann in 1853 in which it was shown that for additive mixtures of coloured lights, only the colour (i.e. the visual stimulus) is relevant and not the spectral composition in determining whether colours are perceived as matching.

2.3.1 CIE Colour Matching Functions

Human colour vision is essentially trichromatic, thus making it possible to unambiguously describe a colour in terms of three variables. Given spectral power data, it is possible to apply three different spectral weighting functions to this in order to derive three such variables. Logically, the spectral sensitivity curves (shown earlier in Figure 2.7) should be used as the basis of these weights; however these were not known with sufficient accuracy at the time the CIE system was developed. Instead, the system was based on a method of trichromatic matching involving the mixing of coloured lights. Experiments conducted by Guild and Wright used red, green and blue matching stimuli. By adjusting the intensities† of these *primary* lights, observers were required to visually match their combined colour to light coming from a fourth test lamp. The amounts of the three matching stimuli required to reproduce a given colour can be used to define that colour and are known as *tristimulus values*. (Note that a match involving tristimulus values does not mean that the spectral power distribution of their light will be the same.)

The choice of primary colours was an arbitrary one, although selecting very different colours did mean that a wide range of test colours could be matched. To match a test colour [C] by mixing primary light sources [R], [G] and [B] we have: C[C] ≡ R[R] + G[G] + [B] (as given by *Grassmann's Laws*). That is, R units of red primary, [R], mixed with G units of green primary, [G], and B units of blue primary, [B], match C units of the test colour [C]. (R, G and B therefore represent the tristimulus values mentioned above.) Unfortunately, such real light sources have physical limitations which means that there will always be some test colours that exist which cannot be matched by a given set of primaries. Mathematically, this can be dealt with by using negative values, e.g. C[C] ≡ -R[R] + B[B] + G[G]. In practice, since light cannot be subtracted, this can be thought of as adding light from one of the primaries to that of the test colour in order to match that of the two remaining primaries. So, taking the previous example, C[C] + R[R] ≡ B[B] + G[G]. Thus, using both positive and negative amounts of light makes it possible to match any test colour.

† Coloured lights mix *additively*, e.g. if red and blue light is mixed, the resultant light contains energy at both the red and blue ends of the spectrum (and so appears purple). *Subtractive mixing* occurs with surface colours such as paint and also with coloured filters. Both of these media absorb light, so a red object absorbs mainly other wavelengths except for red which it either reflects or transmits. Thus, combining red and blue filters would probably result in very little (if any) light emerging from the other side.

In 1931, the CIE used spectrum colours, selecting a red primary at 700nm, green at 546.1nm and blue at 435.8nm. Through their experiments, it was determined what relative amounts of these primaries were needed to match any other spectrum colour. The average results of a small number of observers were used to define the CIE 1931 2° "standard observer" (2° being the angle subtended at the eye by the test field). These are plotted as the tristimulus values $\bar{r}$, $\bar{g}$ and $\bar{b}$ shown in Figure 2.11. The real primaries [R], [G] and [B] were later supplanted by three imaginary primaries [X], [Y] and [Z] such that the corresponding colour matching functions $\bar{x}$, $\bar{y}$ and $\bar{z}$ are always positive. The values of $\bar{x}$, $\bar{y}$ and $\bar{z}$ are computed from $\bar{r}$, $\bar{g}$ and $\bar{b}$ as follows:-

$$\bar{x}(\lambda) = 0.49\bar{r}(\lambda) + 0.31\bar{g}(\lambda) + 0.20\bar{b}(\lambda)$$

$$\bar{y}(\lambda) = 0.17697\bar{r}(\lambda) + 0.81240\bar{g}(\lambda) + 0.01063\bar{b}(\lambda)$$

$$\bar{z}(\lambda) = 0.00\bar{r}(\lambda) + 0.01\bar{g}(\lambda) + 0.99\bar{b}(\lambda)$$

These functions define the colour matching properties of the *CIE 1931 Standard Colorimetric Observer*, often shortened to the *2° Observer*. Using them, it is possible to compute the CIE tristimulus values *X*, *Y* and *Z* of a colour from data describing the spectral power distribution *E* of the illuminant and the reflectance (or transmittance) *R*. Following on from Figure 2.9 earlier, a similar relationship can be defined for tristimulus values which is shown in Figure 2.12. Thus,

$$X = k \int ER\bar{x}\, d\lambda \approx k \sum_{\lambda} E_{\lambda} R_{\lambda} \bar{x}_{\lambda}$$

$$Y = k \int ER\bar{y}\, d\lambda \approx k \sum_{\lambda} E_{\lambda} R_{\lambda} \bar{y}_{\lambda}$$

$$Z = k \int ER\bar{z}\, d\lambda \approx k \sum_{\lambda} E_{\lambda} R_{\lambda} \bar{z}_{\lambda}$$

where λ is taken over the the visible spectrum with wavelengths ranging from 380 to 780nm and

$$k = \frac{100}{\int E\bar{y}\, d\lambda} \approx \frac{100}{\sum_{\lambda} E_{\lambda}\bar{y}}$$

In the 1931 system, Y is referred to as the *luminance factor* (or alternatively *luminous reflectance* or *luminous transmittance*) and is meant to correlate with a colour's perceived lightness. Conventionally, a

Figure 2.11: CIE Colour Matching Functions $\bar{r}$, $\bar{g}$ and $\bar{b}$

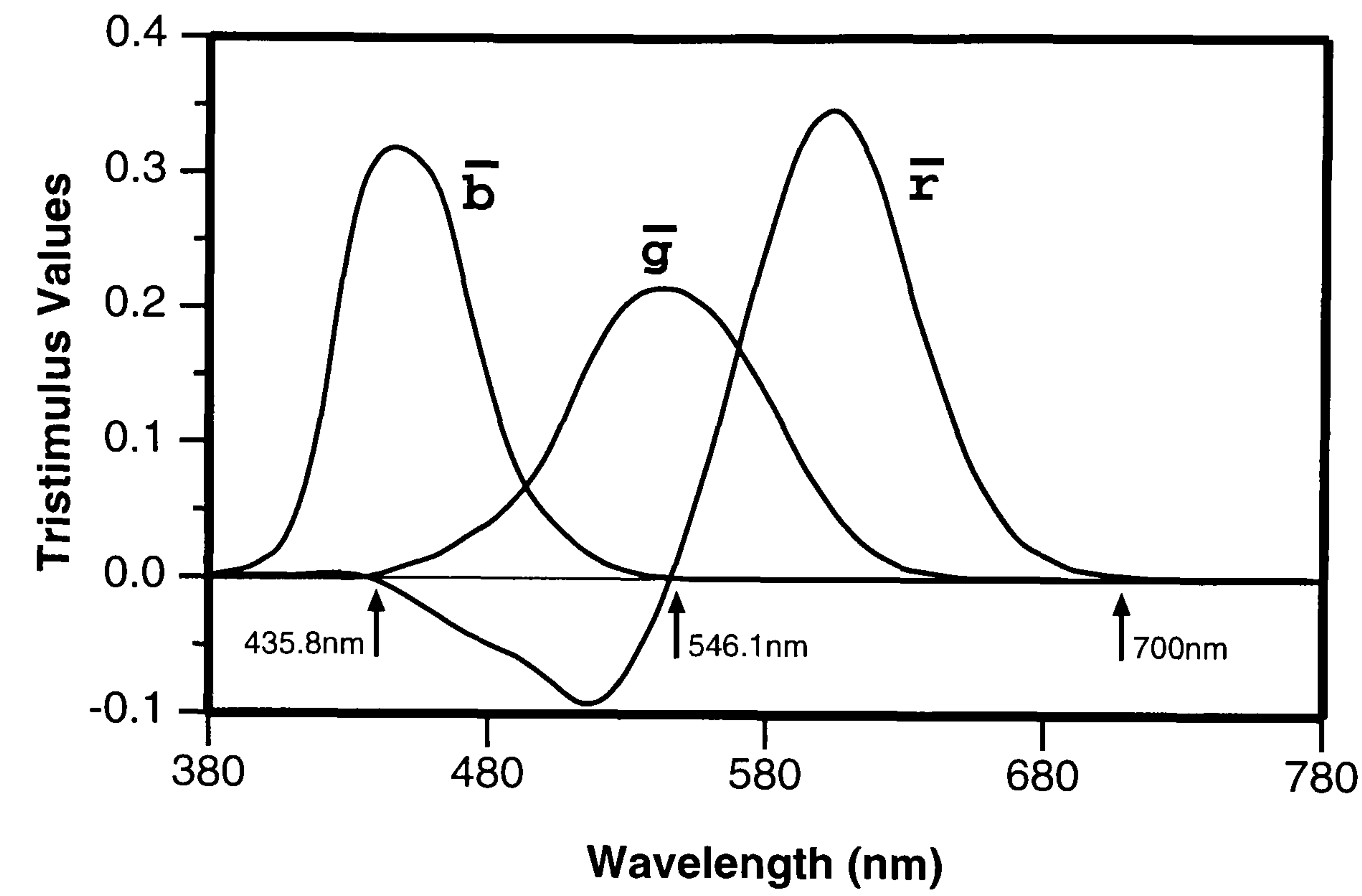
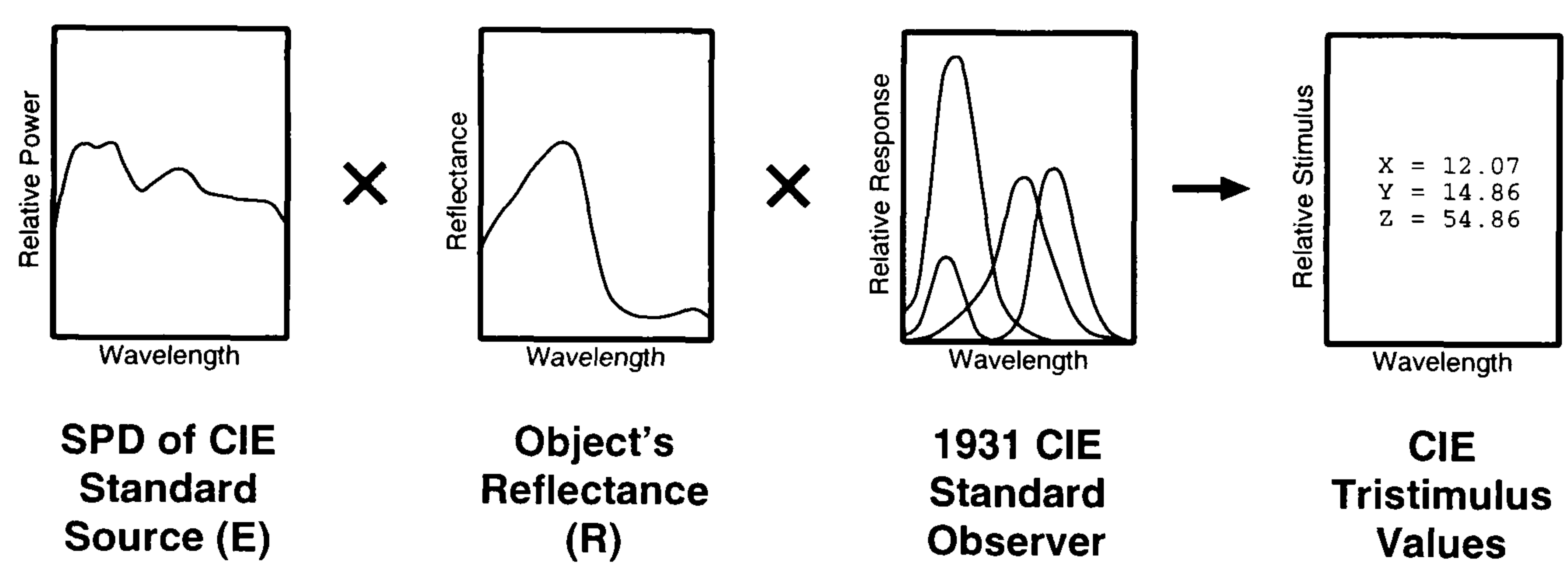


Figure 2.12: Calculation of CIE Tristimulus Values



value of 100 corresponds to a perfect reflecting (or transmitting) diffuser† which is illuminated and viewed under similar conditions. Mathematically, this is achieved through the appropriate choice of constant *k* above. Thus, Y corresponds to the percentage luminous reflection or transmission of a colour sample. The three dimensional nature of tristimulus data makes it difficult to plot. It is therefore common practice to

† A perfect reflecting/transmitting diffuser is one which reflects/transmits all incident light equally strongly in all directions and at all wavelengths throughout the visible spectrum.

represent colours in two dimensions by defining *chromaticity coordinates* as follows:

$$x = \frac{X}{X + Y + Z}$$

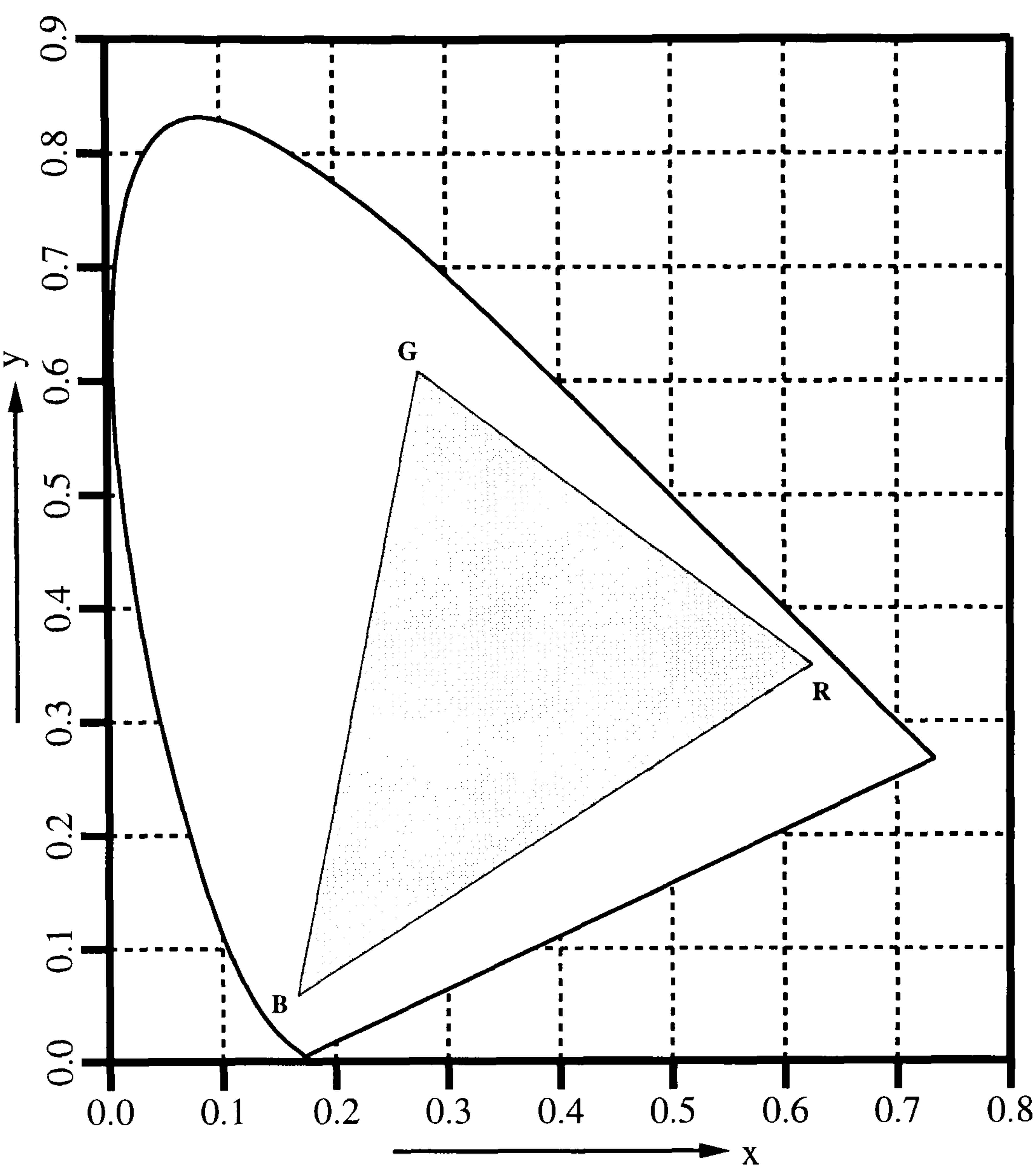
$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

From this, it follows that for all colours $x + y + z = 1$ and hence it is sufficient to specify only two of these chromaticity coordinates. Typically, x and y are plotted in a two dimensional *chromaticity diagram*. Such a diagram is shown in Figure 2.13 which also includes a locus representing each of the spectrum colours. The spectrum locus marks the boundary of real colours. It should be noted that any two dimensional (x, y) point actually represents a series of colours and it is usual to regard the missing factor as the Y tristimulus value so a colour might actually be specified in terms of (x, y, Y). Chromaticity diagrams also have the useful property that if the chromaticity of two lights are plotted, any additive mixture of the two lies along the straight line joining the two points. A further use, as shown in Figure 2.13, is in visualising the gamut (or range) of reproducible colours for a particular display device. In this diagram, the triangle joining points representing the red (R), green (G) and blue (B) monitor primaries marks the boundary of the displayable gamut. One disadvantage of the chromaticity diagram is that it is not visually uniform; equal x- or y- steps do not produce equally perceived colour steps (this is discussed further in §2.3.4).

The 1931 CIE standard observer used a visual angle of around 2° (covering only the fovea). As mentioned previously, the eye's sensitivity to colour varies significantly across the retina. Later, in 1964, the CIE recommended another set of colour matching functions, $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}_{10}(\lambda)$ corresponding to a 10° field of view and known as the *CIE 1964 Supplementary Standard Colorimetric Observer*, or the *10° Observer* for short. Using these new weighting functions, it is possible to compute the tristimulus values X_{10}, Y_{10} and Z_{10} as before. It is recommended in the standard [CIE85a] that the 1964 observer should be used for visual matching fields of greater than 4°. Also an important part of standardisation is the viewing geometry. The ASTM (American Society for Testing Materials) recommendation for both 1931 and 1964 observers [ASTM88a] is that the sample should be illuminated at 45° to the surface and viewed at right

Figure 2.13: Chromaticity Diagram Illustrating Colour Gamut (RGB)



angles to the surface. This is also known as 45/0 geometry.

2.3.2 Colour Measurement

The preceding section introduced the CIE system of colorimetry as a means of numerically describing a colour. This section provides an overview of how practically colour can be quantified. CIE tristimulus values for a colour can be obtained either by visual matching or by instrumental measurement. Clearly, visual matching is less objective and is likely to be much more time-consuming. Modern colour measurement instruments are able to supply CIE XYZ values either by computation from measured spectral power data or by direct measurement using coloured filters. Whatever the method chosen, it is well worth bearing in mind that the final judge of whether colours are indeed correct is the eye.

The measurement of spectral power involves either *photometry* or *radiometry*. In photometry, the amount of *light* emitted by a stimulus is compared to that of a known standard stimulus (frequently a white standard) resulting in ratio data. The instrument used for such measurements is known as a *spectrophotometer*. Radiometry, on the other hand, involves the measurement of absolute *radiant power* and so requires that all of the detectors used at each of the wavelengths have equal sensitivity. Instruments for taking radiometric measurements include *spectroradiometers* and *telespectroradiometers*.

A much simpler and more convenient approach is that taken by colorimeters. These use filtered photocells as light detectors and have three specially designed filters such that their spectral sensitivities closely mimic the CIE colour matching functions (these are also known as *trichromatic colorimeters*). Such instruments are limited by the accuracy of how well the filters are made to correspond to the CIE colour matching functions. Alternatively, either different filters can be used and the measured data transformed mathematically to CIE XYZ or more than three filters can be used to improve accuracy.

One fundamental property of the CIE system is that if two colours have the same tristimulus values and are viewed under the same conditions they should match even though they might have very different spectral reflectance properties. If they do match under one set of conditions but not another, they are said to form a metameric pair. As with observers, colour measurement instruments can also give rise to a form of metamerism — known as *instrument metamerism* — as a result of different instruments having different spectral response curves. These differences arise due to such factors as optical design (illuminating and viewing geometry), bandwidth, light source, measurement range and interval.

2.3.3 Uniform Chromaticity Diagrams

Although widespread in its use, the x, y chromaticity diagram has one important drawback: the spacing of colours within its area is visually non-uniform. This is an inherent property of the CIE system itself which is based on colour matching and is not intended to provide a uniform colour space. The resulting distortion is similar in effect to that seen when world maps are produced by projecting the spherical surface of the earth onto a flat piece of paper. A number of attempts have been made to correct this non-uniformity, although it is only possible to minimise distortion and not eliminate it altogether. In 1960, the CIE proposed the u, v diagram which was later superseded in 1976 by the u', v' diagram (such that $u' = u$ and

$v' = 3v'/2$). The relationship between u', v' and XYZ is given below:

$$u' = 4X/(X + 15Y + 3Z) = 4x/(-2x + 12y + 3)$$

$$v' = 9Y/(X + 15Y + 3Z) = 9y/(-2x + 12y + 3)$$

The resulting chromaticity diagram is known as the *CIE 1976 uniform chromaticity scale diagram*, the *CIE 1976 UCS diagram* or more simply the *u', v' diagram*. As common with all other chromaticity diagrams, this too has the property that additive colour mixtures can be represented by points lying on a straight line connecting the component colours. Because of its uniformity, the u', v' diagram is suitable for such tasks as exploring colour discriminability. The diagram was also used as the basis for the CIE 1976 $L^*u^*v^*$ uniform colour space which is introduced later in §2.4.1.

2.3.4 Limitations of Colorimetry

The CIE system, being based on experimental observations, is fundamentally empirical in nature. The essence of the system has remained unchanged for over sixty years. However, in terms of giving an indication of whether two colours match or not, it can only be applied for a restricted set of conditions (i.e. those in which the viewing conditions are identical). Differences in viewing or measurement geometry, and illumination (which are inevitable in everyday practice) all lead to discrepancies in colour matching. Furthermore, while being useful for colour measurement and specification, it says nothing about how colours will be *perceived*. Neighbouring colours (§2.2.3) or surface media factors such as gloss, texture and non-uniformity of colour all modify the way we see colour. A more recent approach to overcoming these limitations, colour appearance modelling, will be introduced in §2.5.

2.4 ADVANCED COLORIMETRY

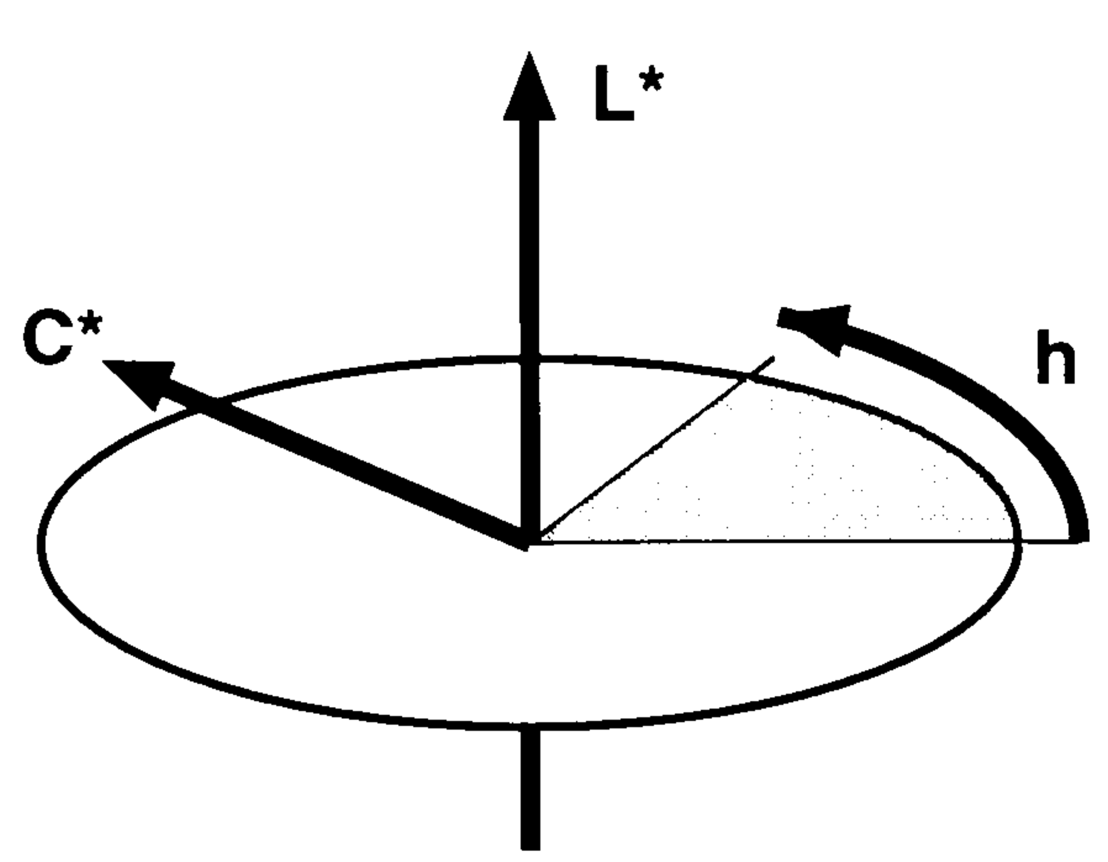
This sections introduces two additional related topics which are not directly part of the core of CIE colorimetry but nevertheless form an essential component of modern colour science.

2.4.1 Uniform Colour Spaces

Whilst chromaticity diagrams, introduced in §2.3.1, have a number of practical applications, their usefulness is limited by their inability to represent anything other than *relative* proportions (as opposed to magnitudes) of tristimulus values. Further, only colours having the same luminance can be plotted on the same diagram. This severely constrains their practical application as, generally speaking, colours will vary in both luminance and chromaticity. To overcome this, two three-dimensional *colour spaces* were recommended by the CIE in 1976.

The first of these, the *CIE 1976* ($L^* u^* v^*$) *colour space* or *CIELUV colour space* consists of the three cartesian axes, L^*, u^*, and v^* plotted at right angles to one another. These coordinates are defined in terms of u', v'† such that a given difference in chromaticity will become smaller as L^* is reduced (as it does perceptually when colours become darker). From u^*, and v^* it is possible to derive two further scales corresponding to chroma (or colourfulness), C^*_{uv} and hue angle, h_{uv}, thus enabling colours to be plotted in a polar space shown in Figure 2.14. The second colour space, the *CIE 1976* ($L^* a^* b^*$) *colour space* or *CIELAB colour space* is somewhat similar, and is defined in terms of CIE XYZ values.† Again, correlates of hue, h_{ab}, and chroma, C^*_{ab}, can be derived.

Figure 2.14: CIELAB/CIELUV Polar Space



Both the CIELUV and CIELAB systems are intended to be used in conjunction with object colours of similar shape and size which are viewed in identical white to mid-grey surroundings. The illuminant's

† Both the CIELAB and CIELUV systems are defined mathematically later in §6.3.

chromaticity should be "not too different" from average daylight. Differences in viewing field size dictates whether the X_{10}, Y_{10} and Z_{10} (10° observer) values should be used rather than X, Y and Z (2° observer). In practice, since CIELUV is a linear transform of x, y, it is often used in applications involving additive colour mixing, such as television. The two systems' approximate perceptual uniformity makes them suitable for expressing differences in colour and it is in looking at this aspect will it become apparent why the CIE chose to define *two* uniform colour spaces.

2.4.2 Colour Difference

Ultimately, the eye is the best judge of whether colours appear to match or not. Despite this, it is very useful to be able to quantify such differences (particularly in industry where many thousands of colour difference assessments may have to be made consistently over a short period of time). A number of different formulæ have been put forward by the CIE and others to compute the colour difference between a pair of samples. By convention, the symbol ΔE is used to denote colour difference.

Both the CIELUV and CIELAB uniform colour spaces which were introduced in the previous section have been used as the basis of colour difference equations. The *CIE 1976* $(L^* u^* v^*)$ *colour difference* or *CIELUV colour difference* formula is equal to the Euclidean distance between the two points in CIELUV space and is defined as follows:

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}$$

This can be further broken down into individual differences ΔL^*, ΔC^*_{uv} and also ΔH^*_{uv} which is a measure correlating with hue defined thus:

$$\Delta H^*_{uv} = [(\Delta E^*_{uv})^2 - (\Delta L^*)^2 - (\Delta C^*_{uv})^2]^{1/2}$$

where ΔC^*_{uv} is the difference in C^*_{uv} between the colours. Hence,

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta H^*_{uv})^2 + (\Delta C^*_{uv})^2]^{1/2}$$

Similarly, the corresponding colour difference measures can be evaluated in the CIELAB space. The *CIE 1976* $(L^* a^* b^*)$ *colour difference* or *CIELAB colour difference* is defined as follows:

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

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta H^*_{ab})^2 + (\Delta C^*_{ab})^2]^{1/2}$$

where the *CIE 1976 a, b hue difference*, ΔH^*_{ab}, is

$$\Delta H^*_{ab} = [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2]^{1/2}$$

The reason why there are two CIE uniform colour spaces and hence two CIE colour difference formulæ is both historical and political. At the time, representatives from different industries argued for different systems, each having characteristics preferred by their use of colour. On the one hand, an earlier measure known as the Adams-Nickerson or ANLAB 40 [Adam42a] colour difference formula was popular in the colourant industries, leading to the similar performing CIELAB formula. On the other hand, the television industry favoured a system which supported additive colour mixtures, hence CIELUV. Studies of the two systems conducted since 1976 have shown that the two perform equally well at representing the perceived magnitude of colour difference.

Another difference formula was adopted in the UK by the Colour Measurement Committee (CMC). The CMC(l: c) equation [McLa86a] defines colour difference as follows:

$$\Delta E = \left[\left(\frac{\Delta L^*}{lS_L} \right)^2 + \left(\frac{\Delta C^*_{ab}}{cS_C} \right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H} \right)^2 \right]^{1/2}$$

where $S_L = 0.040975L^*/(1 + 0.01765L^*)$, unless $L^* < 16$ when $S_L = 0.511$, and

$$S_C = 0.0638C^*_{ab}/(1 + 0.0131C^*_{ab}) + 0.638$$

$$S_H = S_C(fT + 1 - f)$$

$$f = \left(\frac{(C^*_{ab})^4}{(C^*_{ab})^4 + 1900} \right)^{1/2}$$

$$T = 0.36 + |0.4 \cos(h_{ab} + 35)|$$

unless h_{ab} is between 164° and 345°, in which case

$$T = 0.56 + |0.2 \cos(h_{ab} + 168)|$$

The constants l and c (*lightness* and *chroma* weights) used in the equation are such that when both are set to unity, the equation is most suitable to predicting *perceptibility* of colour differences (i.e. whether perceived colour differences between a standard and two batch samples are equal or not). As an example, the perceived colour difference between two pairs of samples might appear the same, however one pair could be regarded as having an unacceptable difference, perhaps because hue or chroma differences are seen to be more critical than that of lightness. For quantifying *acceptability* (i.e. whether the difference between standard and batch should result in a pass or fail of the batch), it is usual to set l to two and c to one, thus making the formula more tolerant to lightness variations.

In addition to the above three, yet more difference formulæ exist such as JPC79 [McDo80a], BFD [Luo87a] and Marks & Spencer [Tayl77a] although many are either proprietary or defunct. There have also been more recent efforts made by both ISO and the CIE to create a standard measure for certain applications although the fact still remains that colour difference units are not interchangeable between different formulæ.

2.5 COLOUR APPEARANCE

It was stated in §2.3.4 that the CIE system of colorimetry is limited in that it is unable to give a clear indication as to whether two colours viewed under different conditions will match. (Colorimetric data is essentially meaningless for dissimilar conditions.) Unfortunately, such differences are inevitable for many practical applications. Despite its success in gaining international acceptance, the CIE system does not take into account the way in which colours are actually perceived. To recap, changes in media, neighbouring colours, illuminant or illumination level all play a critical role in colour perception. What is missing from conventional colorimetry, therefore, is a model of colour vision which incorporates viewing parameters in order to describe colour unambiguously in a viewing condition independent manner. Several *colour appearance models* have been proposed which claim to do just this, including RLAB [Fair93a] and those of Nayatani [Naya90a] and Hunt [Hunt94a]. These are still undergoing a process of progressive refinement and so, at least at present, no single model deals reliably with all possible viewing parameters.

A key element of colour appearance which needs to be taken into account is adaptation (first introduced in §2.2.3). Colours can often appear very differently for the first few seconds than they do after the observer has had time to adapt to the viewing field. The visual response produced by the cone receptors is dependent not only on the magnitude of the stimulus but also on the eye's state of adaptation. Furthermore, the nature of adaptation is different for related and unrelated colours [Hunt92a]. In this context, colours that are perceived as belonging to areas seen in relation to other colours are defined as being *related.* That is, the colours are not viewed in isolation from other colours. Luminous colours (e.g. light sources) are typically perceived as being *unrelated.* Non-luminous objects are generally perceived as related colours. A notable exception to this rule is a CRT screen (such as a TV or computer monitor). While the display is self-luminous, within the picture area itself, related colours are perceived for those scenes depicting illuminated (i.e. non-luminous surface colour) objects.

Chromatic adaptation due to different light sources is not always complete (and is in fact less so for more chromatic sources such as tungsten lighting). This can lead to such phenomena as the *Helson-Judd* effect whereby white colours appear to be tinted with the colour of the illuminant and dark greys appear coloured with the complementary hue. One simple (and approximate) means of predicting chromatic adaptation is via a *Von Kries transform* [Hels52a] which ignores the Helson-Judd effect, assuming that a white colour remains white under different lighting conditions. It also assumes that chromatic adaptation can be represented by the cone responses (ρ, γ, β) scaled by factors which lead to the reference whites (ρ_W, γ_W, β_W) producing identical signals in all states of adaptation. Hence, two colours (known as *corresponding colour stimuli*) should appear to match each other if

$$\rho / \rho_W = \rho' / \rho'_W, \quad \gamma / \gamma_W = \gamma' / \gamma'_W, \quad \beta / \beta_W = \beta' / \beta'_W$$

This type of transformation is also known as a *white point transform.*

The above really only just begins to scratch the surface of the topic of colour appearance and colour appearance modelling. Clearly, our colour vision is highly complex in nature and at present our understanding of it is far from complete. Having said that, applying a colour appearance model to existing CIE colorimetry greatly extends the range of applications for which colour and colour phenomena can be quantified.

2.6 COLOUR NOTATION

Having now covered the topics of colour measurement and colour appearance we now move onto the subject of describing colour. In everyday language, one might describe a colour as appearing red but unfortunately one person's idea of red does not (necessarily) correspond to another's. Such nomenclature is typically imprecise, highly subjective and also differs according to application or culture. (For example, Eskimos have many more names to describe the subtle variations in the colour of snow.) What is required, therefore, is a precise, unambiguous language for describing colour. To begin with, a colour stimulus can be broken down into a number of perceptual attributes which are defined [CIE87a] as follows:

Hue The attribute of a visual sensation according to which an area appears to be similar to one, or to combinations of two, of the perceived colours red, yellow, green and blue.

Brightness

The attribute of a visual sensation according to which an area appears to exhibit more or less light. (Related adjectives are *bright* and *dim.*)

Lightness

The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting. Note: only related colours exhibit lightness. (Related adjectives are *light* and *dark.*)

Colourfulness

The attribute of a visual sensation according to which an area appears to exhibit more or less of its hue. Also known as *chromaticness.*

Chroma

The colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting. Note: chroma can only be applied to related colours. (Related adjectives are *weak* and *strong.*)

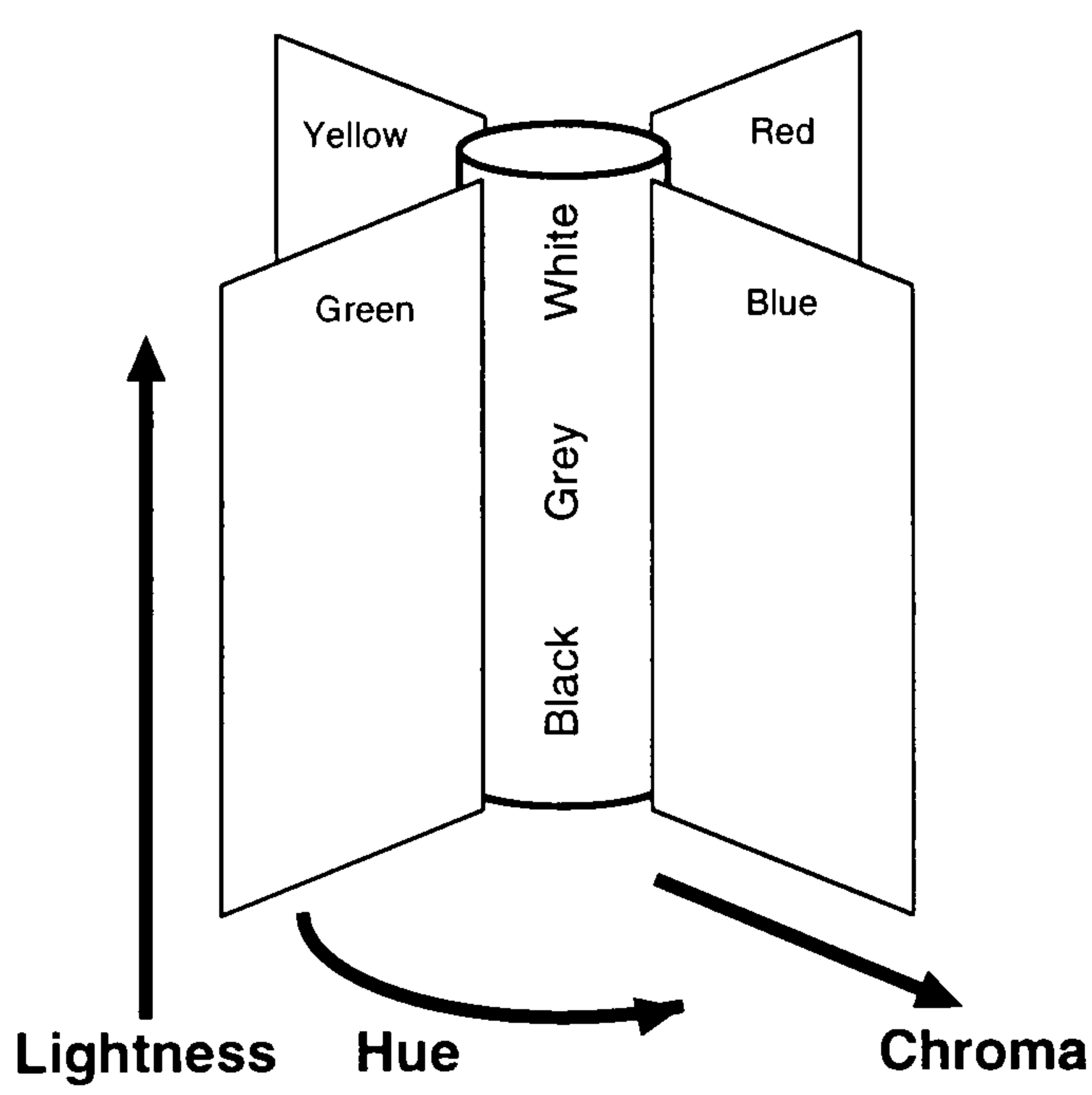
Saturation

The chromaticness or colourfulness of an area judged in proportion to its brightness.

Recall from §2.3.1 that, owing to the trichromatic nature of vision, colour is a three dimensional phenomenon and so it should be obvious that uniquely describing a colour requires at least three such attributes.

Together, three attributes can be used to form a *colour space* of which Figure 2.15 forms a basic example. In this diagram, similar to many other systems for colour notation, there is a central vertical axis consisting of a sequence of neutral (or achromatic) colours ranging from black through grey to white. Moving further away from this axis, colours become stronger, i.e. they increase in chroma and moving around this axis, colours change in hue (according their spectral order). Different notation systems use different notional attributes such as colourfulness instead of chroma, although even systems supporting the same basic types of perceptual attribute are unlikely to have scales which directly correspond. However, where most systems significantly differ (at least from a user's point of view) is in their way of describing hue. Some of the different ways for ordering colours are categorised next according to their organisational basis.

Figure 2.15: A Colour Space with Attributes Hue, Lightness and Chroma



2.6.1 Sample-Based Colour Order Systems

One popular means of organising colour is through the use of collections of physical colour samples. These are often used by industry to illustrate material or pigment product ranges such as paint, ink or fabric. Such systems can range from unstructured or random collections with no obvious guiding principle to ordered colour atlases arranged on the basis of equal visual perception. (Random in this sense is taken to mean the colours are arranged such that it is not possible to deduce the appearance of colours which are intermediate to the system's samples.) Another possibility is ordering colours on the basis of colourant behaviour. An example of such an arrangement, the Pantone system [PANT90a], is based on the mixture of printing inks used in the graphic arts.

2.6.2 Colour Order Systems Based on Colour Mixing

Mixing known amounts of colourants or coloured lights provides one predictable means for obtaining colours and hence they can be specified in these terms. This, of course, is the basis of CIE colorimetry. Another well known system, the Ostwald System [Ostw33a, Jaco48a], uses results obtained by disc colorimetry† to describe colours in terms of their *white*, *black* and *full colour* contents. Because of the Ostwald System's emphasis on these scales, its use is convenient for those who work with mixtures of a coloured pigment with black and white pigments. In addition, the system was designed to give equivalent colour difference between neighbouring samples.

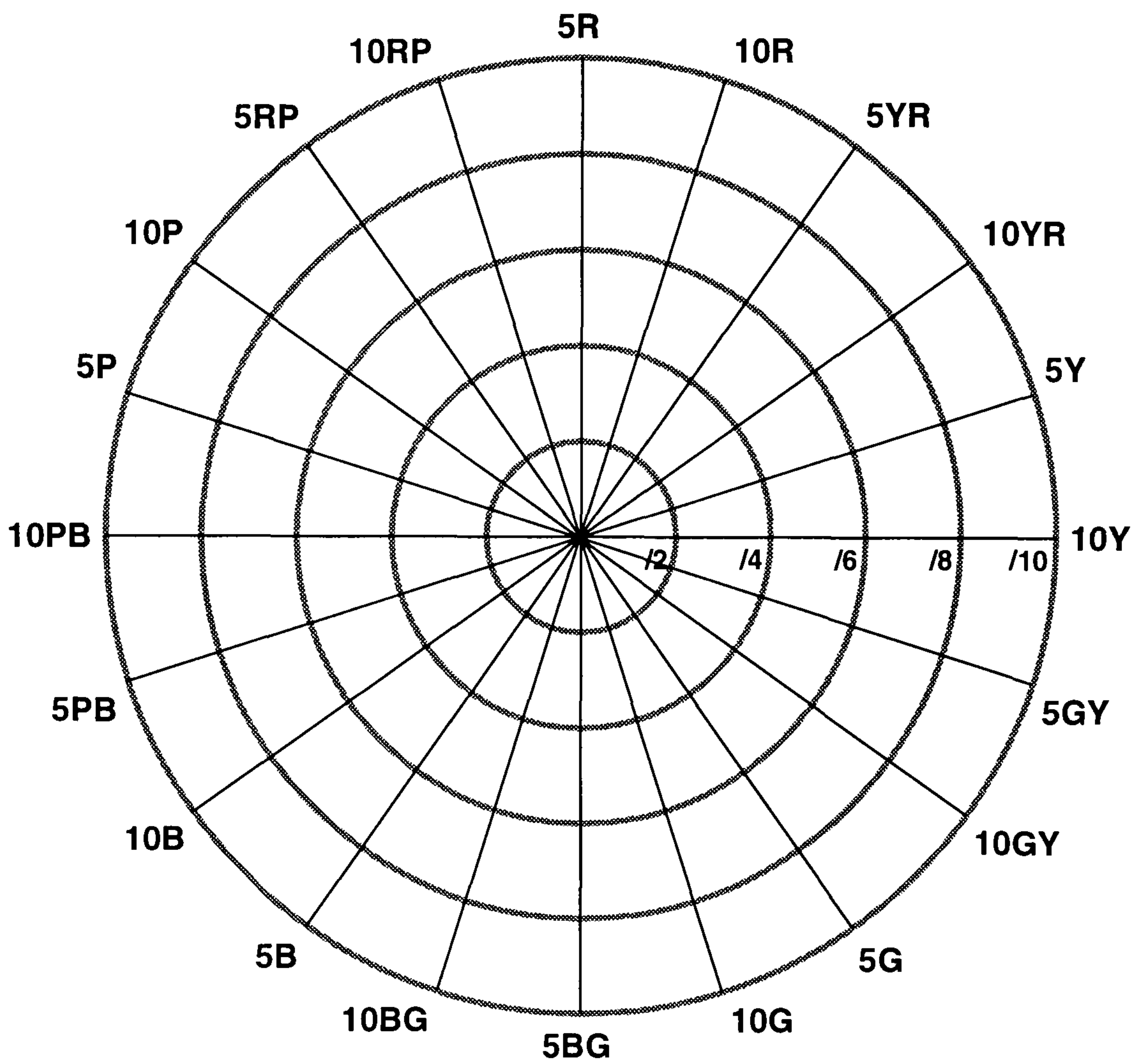
2.6.3 Colour Order Systems Based on Equal Visual Perception

One of the oldest and best known colour order system is the *Munsell System* [Muns29a, Muns36a]. This system was originally developed by the artist A.H. Munsell in 1905 using the guiding principle of equal visual spacing between each of its three attributes: Munsell Hue, Munsell Value and Munsell Chroma (HVC). The arrangement of the Munsell Hue scale, shown in Figure 2.16, is based on five principal hues. These are red (5R), yellow (5Y) green (5G), blue (5B) and purple (5P). Intermediate hues are formed from two neighbouring hues, e.g. 2.5BG (which is between 5BG and 10G), according to a zero to ten scale. The Munsell Value scale corresponds to the visual percept of lightness and ranges from zero (black) to ten (white). Munsell Chroma ranges from zero (neutral) up to around twenty, although the exact value is Hue

† Disc colorimetry [Maxw60a] involves a rapidly spinning disc which contains segments of different colours. The speed of rotation gives the illusion of a solid colour which is effectively "mixed" from the colours of the other segments in proportion to their segment size.

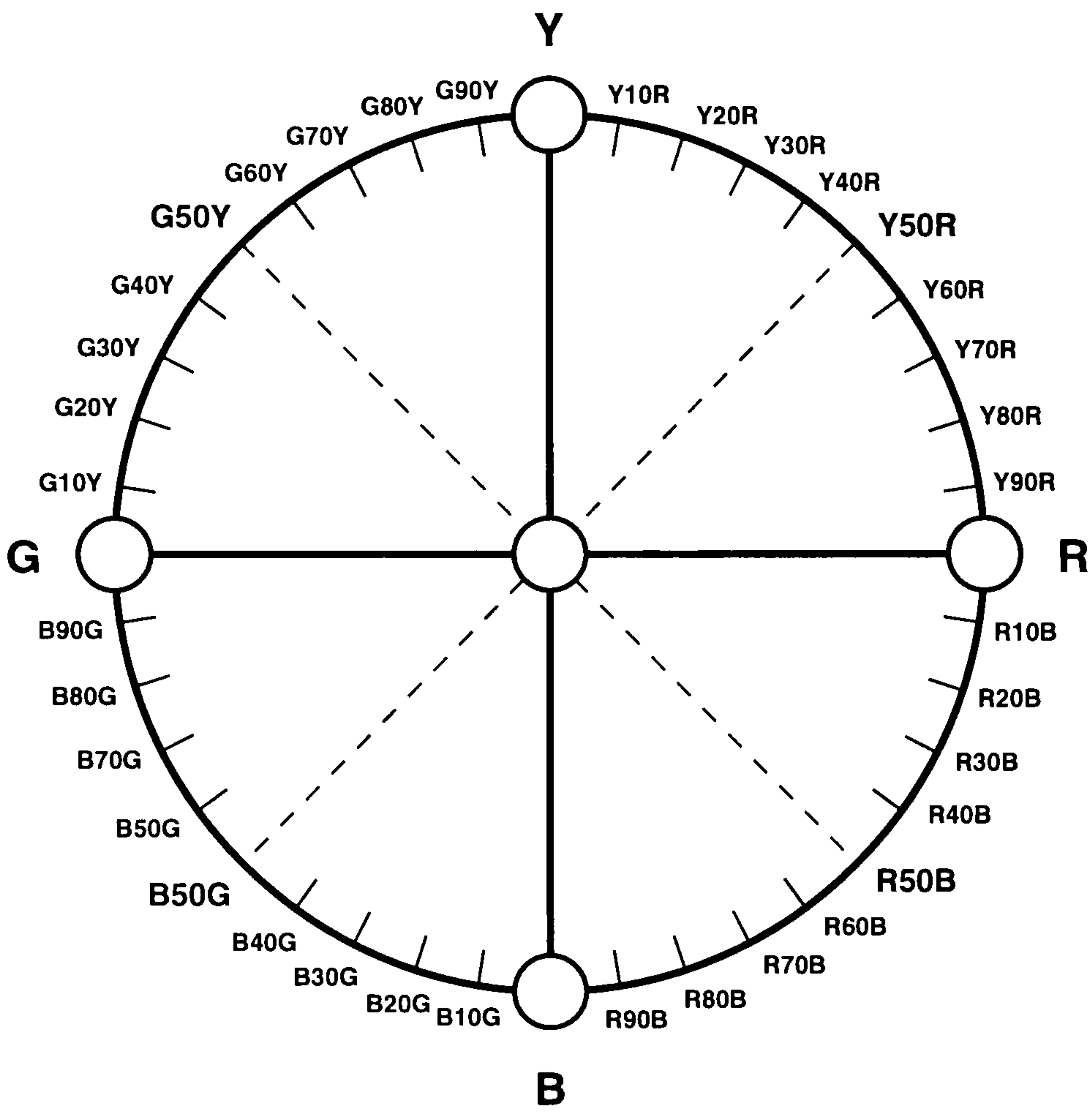
and Chroma dependent. The notation used to specify a colour in Munsell terms is Hue followed by Value and Chroma, e.g. "7.5PB4/7." In physical form, the *Munsell Book of Color* is organised as pages of constant Munsell Hue with coloured chips arranged in a grid of Chroma changing horizontally and Value changing vertically. The system is used extensively throughout the USA and far east countries.

Figure 2.16: Arrangement of Hues in the Munsell System



Another system, which has been proposed as a standard in Scandinavia, is the *Natural Colour System* or NCS [Hard81a]. The system had its origins with the work of the German psychologist Ewald Herring in 1875. Herring proposed that, despite the trichromatic nature of vision, there are four *unique hues*: red, yellow, green and blue, as shown in Figure 2.17. Any chromatic colour can therefore be represented as a combination of two (or less) of these hues. Hues such as red and green or yellow and blue cannot be perceived together in the same colour and are known as *opponent hues*. Along with black and white, NCS describes colours in terms of their *redness* (r), *yellowness* (y), *greenness* (g), *blueness* (b), *whiteness* (w) and *blackness* (s) using a percentage scale. Blackness and whiteness describe the resemblance of a stimulus to a perfect black or white respectively. The scale is such that $r + y + g + b + w + s = 100$. Another scale, *chromaticness* (c), is simply the sum $r + y + g + b$ (hence $s + w + c = 100$) and is zero for achromatic colours. Chromaticness describes the resemblance of a test colour to a colour of the same hue having the maximum possible chromatic content.

Figure 2.17: Arrangement of Hues in the Natural Colour System



A number of other systems exist which are worth a brief mention, including OSA, Coloroid and DIN. The OSA Uniform Colour Scales System [MacA74a] aims to provide a geometrically uniform spacing with perceptually equal colour differences throughout its colour space. The system is organised as a close packing, regular rhombohedral lattice and arranged according to the attributes *lightness* (L), *greenness-redness* (g) and *yellowness-blueness* (j). Another colour system specifically aimed at architects, called *Coloroid* [Nemc87a], was developed in Hungary by Antal Nemcsics. The system aims to achieve an "aesthetically even" spacing, rather than attempting to separate on the basis of colour difference (as in the NCS or Munsell systems). Coloroid notations can be readily calculated from CIE x, y chromaticity coordinates and luminance factors, Y, using simple formulæ. This is unlike the majority of other colour order systems which are defined in terms of fixed aim points (usually corresponding to colour samples in a colour atlas). The DIN (Deutches Institut für Normung) system [Rich86a] was devised by Manfred Richter and co-workers in Germany. The system's three variables, *hue* (T), *saturation* (S) and *darkness* (D) have equal visual spacing and are written in the form T:S:D. The hue scale comprises twenty-four principal hues, ranging from value T=1 for yellow, progressing through red, purple, blue and green to value T=24 for yellow-green.

2.6.4 Advantages and Disadvantages of Colour Order Systems

The adoption of physical colour order systems for the purposes of colour selection, specification and measurement is both popular and widespread. Their use has a number of advantages including versatility, ease of use and understandability. Conversely, they are limited by having relatively few samples with gaps between them requiring visual interpolation. They are also constrained by the viewing conditions (in particular, the illuminant) with which they can be used. Individual colours may be less accurate than is desired owing to manufacturing tolerances or aging of the samples. Furthermore, it is likely that some samples cannot be reproduced as a result of gamut constraints. Finally, a very important limitation to their success is the fact that there are very many different systems in use with no simple or readily available means of transferring colour information between them.

2.6.5 Other Systems

As already mentioned, colour order systems tend to be based on physical samples. Alternative schemes for colour notation do exist. In §2.4.1, the CIELAB and CIELUV uniform colour spaces were introduced and these can be used as the basis of mathematically defined notation systems. Another approach taken by *colour naming systems* is using a universally understood natural language. Examples of this include the Universal Colour Language [Kell76] and ISCC-NBS [NBS65a]. Such languages permit colours to be described with varying degrees of accuracy and typically work by partitioning an existing colour space (such as Munsell) into solid regions which correspond to a particular colour name.

2.7 COLOUR REPRODUCTION

Previously, it has been shown how colour can be quantified, however this is practically of most use if its description can be used to define how the colour may be reproduced. In this final section, a survey is taken of the technology currently available for the computer-controlled reproduction of colour. Recent advances in technology and manufacturing have meant a dramatic increase in performance together with a reduction in cost for such devices. Of these, by far the most prolific is the colour visual display unit or VDU, however both printing and input technologies will also be briefly mentioned.

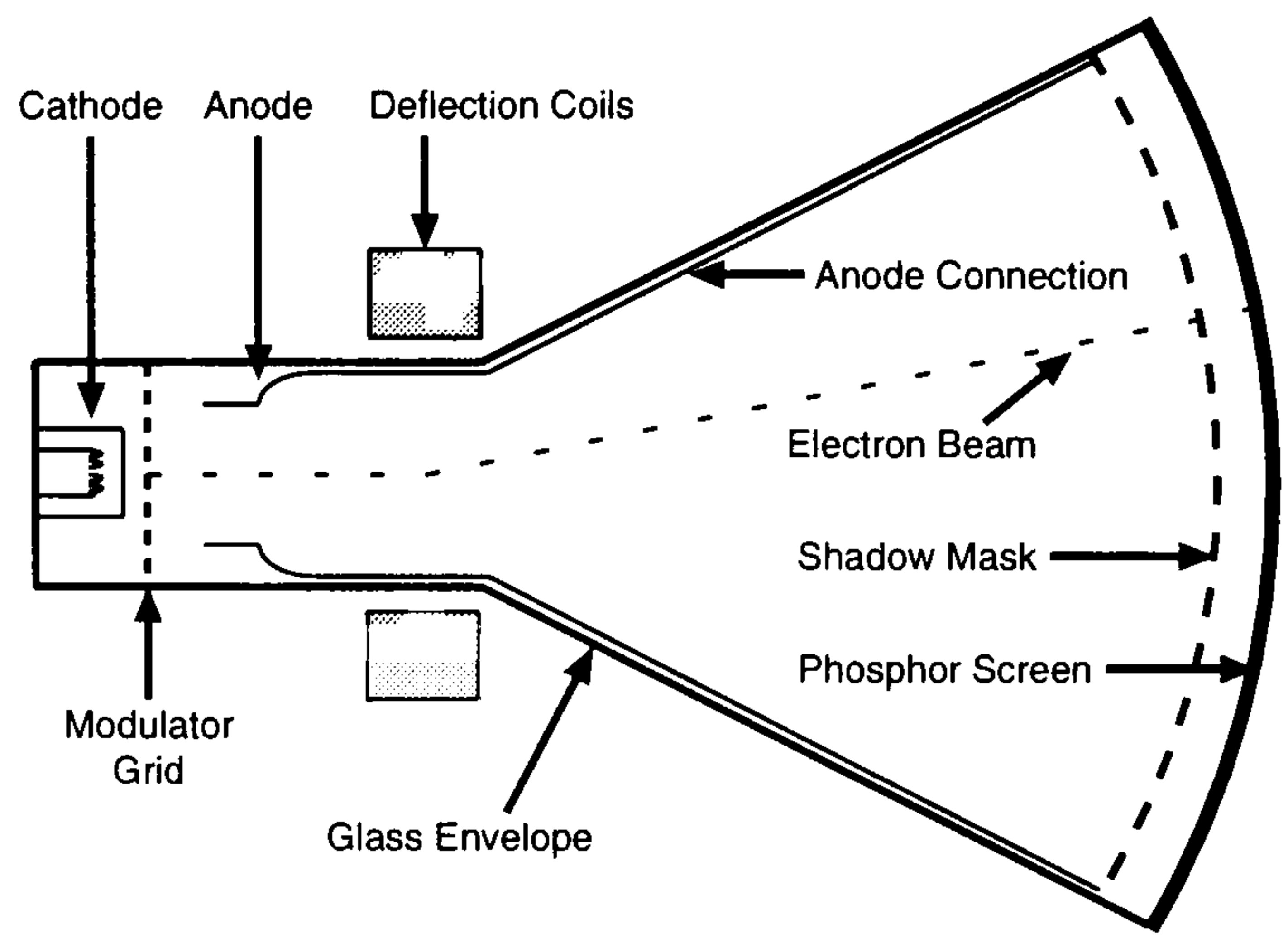
2.7.1 Display Technology

The Cathode Ray Tube

Colour television and colour computer monitors are both based on the cathode ray tube (CRT) which was developed in the early 1950s. The CRT, pictured in Figure 2.18, consists of an evacuated glass tube. At the rear of this, a heated material (forming the *cathode*) continuously produces electrons through a process known as *thermionic emission*. Electrons, being negatively charged, are accelerated towards a positively charged *anode*. The anode is kept at a highly positive potential relative to the cathode by the application of a high voltage of the order of several kV. Subsequently, the electrons strike the phosphor coated inside of the screen and release energy as visible light. Directional control of the electron beam (and hence determining where electrons hit the screen) is carried out by the *focusing system* and *deflection coils*. The intensity of light that is emitted is governed by the voltage difference between the cathode and *control* or *modulator grid*.

In colour CRTs, there are three separate electron "guns" (i.e. systems for emitting electrons), each directing electrons to the screen. The screen is coated with three different types of phosphor which emit either red, green or blue light. The different phosphor types are positioned in a series of patterns of repeating dots forming, for example, a triad or column of points. Ideally, electrons from one gun strike only one colour of phosphor (hence the guns are often referred to as "red guns," etc. even though they possess no intrinsic colour properties). This is achieved through the use of a *shadow mask* which blocks electrons from reaching all but the desired phosphor (thus creating an electron "shadow") exploiting the parallax of

Figure 2.18: Simplified Cross Section of a CRT



the three electron guns. When viewed from a distance, the red, green and blue (RGB) dots form solid colours in the same way as halftone ink dots do for print. Over time, the deflection of the electron beams are adjusted so that they pass by each phosphor point on the screen (which may or may not be illuminated). This is done in in a zig zag fashion known as a *raster scan.* Typically, this cycle is repeated several tens of times per second at a frequency known as the *refresh rate.* The persistence of both the phosphors and our vision gives the appearance of a steady, (almost) flicker-free image.

Differences in phosphors and adjustment of the control grid mean that identical video signals input to two different monitors can yield vastly different colours. Standardisation on the use of primary phosphors is one common approach to reducing this difference. In addition, CRTs are often described in terms of their *white point*, i.e. the colour produced by driving the display with equal red, green and blue signals. The white point is usually expressed in terms of a correlated colour temperature such as D_{93}. By adjusting signal sensitivities, it is possible to adjust the white point, however the range of colours is fundamentally constrained by gamut limitations of the phosphors.

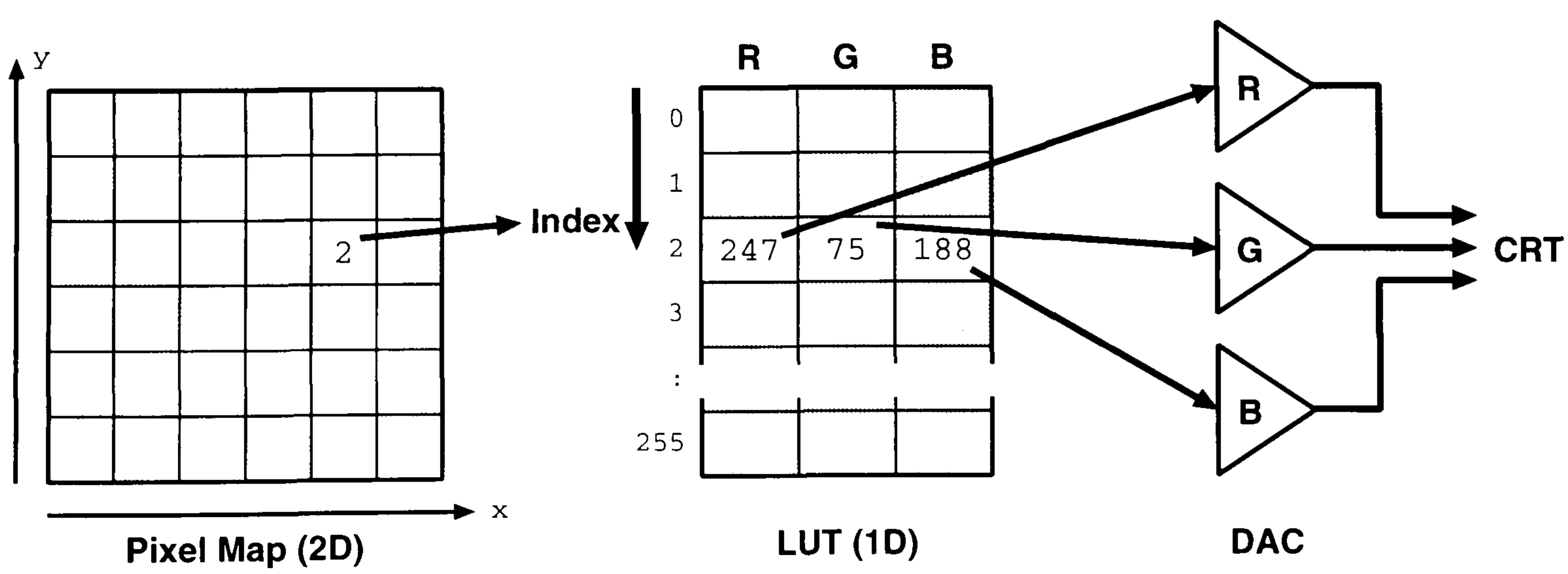
The Frame Buffer

Raster scan displays such as the CRT require constant refreshing to maintain an image on the screen. Rather than having the host computer constantly control this directly (which would be very inefficient), the usual arrangement is to have what is known as a *frame buffer* between the computer and display controller.

In essence, this is an area of high speed memory which contains the two dimensional screen image to be shown. The display controller reads from this memory in order to refresh the screen and the host computer writes to it in order to change the contents of the displayed picture. The size and organisation of the memory determines the resolution of the picture, the smallest addressable cell being referred to as a picture element or *pixel.* Each pixel can correspond to one or more bits in the frame buffer's video memory. The digital values stored in this memory are converted to analogue signals by a *digital to analogue converter* (DAC) which are required by the CRT and its controlling circuitry.

Single-bit pixels are typically used for black and white display systems. Most high performance colour displays use eight-bit DAC values to represent the various voltage levels to drive each of the RGB guns, thus requiring a total of twenty-four bits per pixel, but yielding over sixteen million (i.e. 2^{24}) different colours. (It should be emphasised at this point that equal steps in DAC values do not produce equal steps in luminance.) An alternative approach used by many low cost colour systems is to use a single byte (eight bits) per pixel. Rather than directly specifying the RGB DAC values to use, this value is used as an index into a 256 element look up table (LUT). The LUT entries are writable and contain a twenty-four bit value that is used to drive the DACs — see Figure 2.19. Although this limits the display to a maximum of 256 different colours, each of these colours still has the same twenty-four bit precision as before. Furthermore, they are often much faster as less information has to be moved around when manipulating images.

Figure 2.19: Operation of Frame Buffer Using an 8-bit LUT



Other Display Technology

Although CRT remains the most prevalent display technology, there are currently several other alternatives. Liquid crystal displays (LCD) are becoming popular, particularly for those applications requiring low power or portability. The basic LCD element acts as an optical shutter, either allowing light to be transmitted or blocking it. The source of light is either reflected ambient light or back lighting. To produce colours, the majority of displays have red, green and blue coloured filters over three subpixels. Another technology which shows some promise is the use of lasers. The main advantage of these is that they provide high resolution and very high luminance levels (and hence yield larger colour gamuts).

2.7.2 Printing Technology

Colour hardcopy devices, like their colour display counterparts, are becoming cheaper and more powerful. Many different colour printing technologies currently exist including:

- *Ink Jet* — Tiny droplets taken from a reservoir of coloured ink are transported through the air to the printed medium. A number of ink delivery mechanisms are used involving pressure, thermal vapourisation or electrostatic charge.
- *Thermal Transfer* and *Dye Sublimation* — In thermal transfer printing, the print head applies heat to a transfer ribbon causing wax-like ink to be melted. Pressure from the print head forces molten ink into the surface of the paper in a pattern of dots. The dye diffusion and dye sublimation processes work in a similar way; however, due to differences in substrate, the dye colourant is made to diffuse into the media. This diffusion process can be controlled with much greater precision than with ordinary thermal transfer.
- *Electrophotographic* (laser printers) — These involve electrostatically charging a photoconductive surface (usually a drum) and exposing it to patterns of light which cause a selective discharge. Toner particles are then attracted by the charge and are transferred to paper before being fused by heat, pressure or solvent.

These technologies typically use cyan, magenta, yellow and (optionally) black pigments and are either single- or multi-pass in terms of applying pigment. Colour is deposited either in fixed dots (*bilevel* printing) or in variable amounts (*continuous tone*). The latter is typically superior, leading to photographic quality images. Bilevel imaging is often cheaper but in order to produce gradations of shade requires the use of halftone techniques. This involves alternating patterns of coloured dots to give the appearance of solid colour at the expense of a reduced spatial resolution. Printer colour gamut is dependent on the (subtractive) printing primaries used and also the colour of substrate.

2.7.3 Colour Reproduction Objectives

Finally, in concluding this section on colour reproduction, we summarise different criteria that can be used when reproducing colour. As already stated, the most critical test of reproduced colours is the judgement of the person viewing them, however a number of objective and quantitative methods have been proposed [Hunt87a] including:

Spectral Colour Reproduction

This requires matching the original reflectance curve (or relative SPD for luminous colours) in order to yield an illuminant independent match. While such a match would also eliminate metamerism, in practice it can be difficult to achieve.

Colorimetric Colour Reproduction

Matches in which colours have the same CIE chromaticities and relative luminances fall under the category of colorimetric reproduction. This type of matching is typically used for reflection prints, although matching samples are most likely metameric.

Exact Colour Reproduction

In addition to having identical chromaticities and relative luminances, exact colour reproduction requires that the absolute luminances of colours in the original and copy also be equal. Provided that the state of adaptation of the observer was the same for both original and copy (i.e. viewing conditions — in particular, the illuminant — must be the identical), the two images would appear to be the same.

Corresponding Colour Reproduction

This is defined as being a reproduction in which the chromaticities and relative luminances of the colours, when seen under picture viewing conditions, have the same appearance as the original colours would have if they were illuminated to produce the same absolute luminance level. This type of reproduction is more likely to be practically realisable since it does not constrain the viewing conditions to use the same illuminant.

Preferred Colour Reproduction

This type of colour reproduction aims to give a more "pleasing" result to the viewer in order to make flesh tones or other colours seem more appealing. As such, colours do not appear to be equivalent to the original.

The type of colour reproduction required is application-specific, depending on what is trying to be achieved. For many cases, preferred reproduction is used because a pleasing appearance is usually the most important criteria (particularly in the graphic arts). The number of applications requiring spectral colour reproduction is likely to be quite small, which is fortunate since this type of colour matching can be extremely difficult to achieve.

2.8 CONCLUSION

In this chapter, colour science and related technologies have been introduced. Fundamentally, a colour stimulus is defined to be the product of the illuminant's SPD, the object's reflectance or transmittance, and the spectral sensitivity of the observer. It was seen that the basis for colour science is the (empirical) CIE system of colorimetry in which colour can be quantified numerically. Limitations in conventional colorimetry restrict its use to conditions involving identical viewing conditions and say nothing about how colours are actually perceived. This, then, points the way forward to be the application of models of colour appearance to expand the scope and usefulness of the CIE system. It was seen that there now exist numerous colour notation systems, each of which is sufficiently different to make one notation incompatible with that of another system. Also evident was the increasing number and performance of devices currently available for colour reproduction. Future directions in this field are likely to involve greater precision and stability of colours together with an increased colour gamut.

Chapter Three
Colour in Design

CHAPTER THREE: COLOUR IN DESIGN

3.1 INTRODUCTION

Colour control is an important issue in industrial design. Many industries such as clothing, furnishing and cosmetics are heavily dependent upon the market's perpetually changing colour preferences for their very existence. Furthermore, their success in business relies on being able to accurately forecast future colour trends and respond rapidly to new directions. One way to decrease response time is through the application of information technology to the design process. As computer-aided design (CAD) systems become more powerful and affordable, there is the expectation of accurate colour reproduction across various media (e.g. colour hardcopy or scanners). However, the reality is often *poor* colour fidelity between display and output resulting in the overhead of painstaking manual colour matching at each stage of colour communication. This is frequently very time consuming and reduces confidence in making *any* colour-critical decisions based on anything but physical samples or full mock-ups of the final design. Mistakes or changes made at any stage can be costly.

In this chapter, a detailed study is made of the typical processes involved within one particular domain: *textile garment design*. The reason for this choice of domain is that it is one in which colour appearance across multiple media is important and in which the communication of colour often needs to take place. In particular, the requirements for high colour fidelity are particularly demanding (as will be seen shortly). The study is based on a series of interviews held with designers and colourists from several design centres. These interviews were conducted informally and notes were taken and later written up as a set of reports (verified by the same designers) given in appendices A-F. (For reasons of confidentiality, certain company-specific detail has been omitted, however this does not in any way detract from the conclusions that are later drawn.) The principal objectives of these visits were to establish an understanding of:

(1) the overall garment design process and

(2) the particular colour selection, communication and control tasks that occur within this process.

A tertiary aim was to investigate how CAD systems were being used in relation to (1) and (2) above.

An overview of the findings is given in the next section, followed by a survey of the designers' application of CAD technology. Finally, a summary of the more important findings with regard to their use of colour is presented together with a list of the required elements necessary to solve the problems or limitations of their current procedures.

3.2 SUMMARY OF THE DESIGN PROCESS

The series of visits to six textile fashion design centres (each summarised in appendices A through F) were undertaken primarily to gain an understanding of the garment design process and to identify where colour plays an important role. Of these visits, two of the designers interviewed were colourists and the remainder were directly involved with garment design. The colourists are responsible for the specification of colour palettes, whilst the garments designers are each involved in distinct clothing sectors (i.e. ladieswear, menswear, lingerie and leisurewear). Hence, it was possible to identify both common aspects and individual differences between them. It was encouraging to find that there was a high degree of commonality between their design processes. This study is not intended to be a complete account of every facet of textile fashion design. One particular area not covered is fabric design and type prediction; this occurs in parallel with the prediction of colour trends. (However, this should not be of great concern: those colour experts interviewed appeared to conduct the majority of their tasks without the need for explicit consideration of such fabric predictions — if, indeed, they are used at all.)

3.2.1 Seasonal Design

Essentially, the garment industry produces goods for *two* distinct seasons: spring-summer and autumn-winter. Although the designs created for each season will be dissimilar (e.g. different materials are used and different colours are considered to be appropriate), the fundamental design processes are broadly the same. For the purposes of this discussion, the spring-summer 1992 season is considered, this being that which was under development during the design visits.

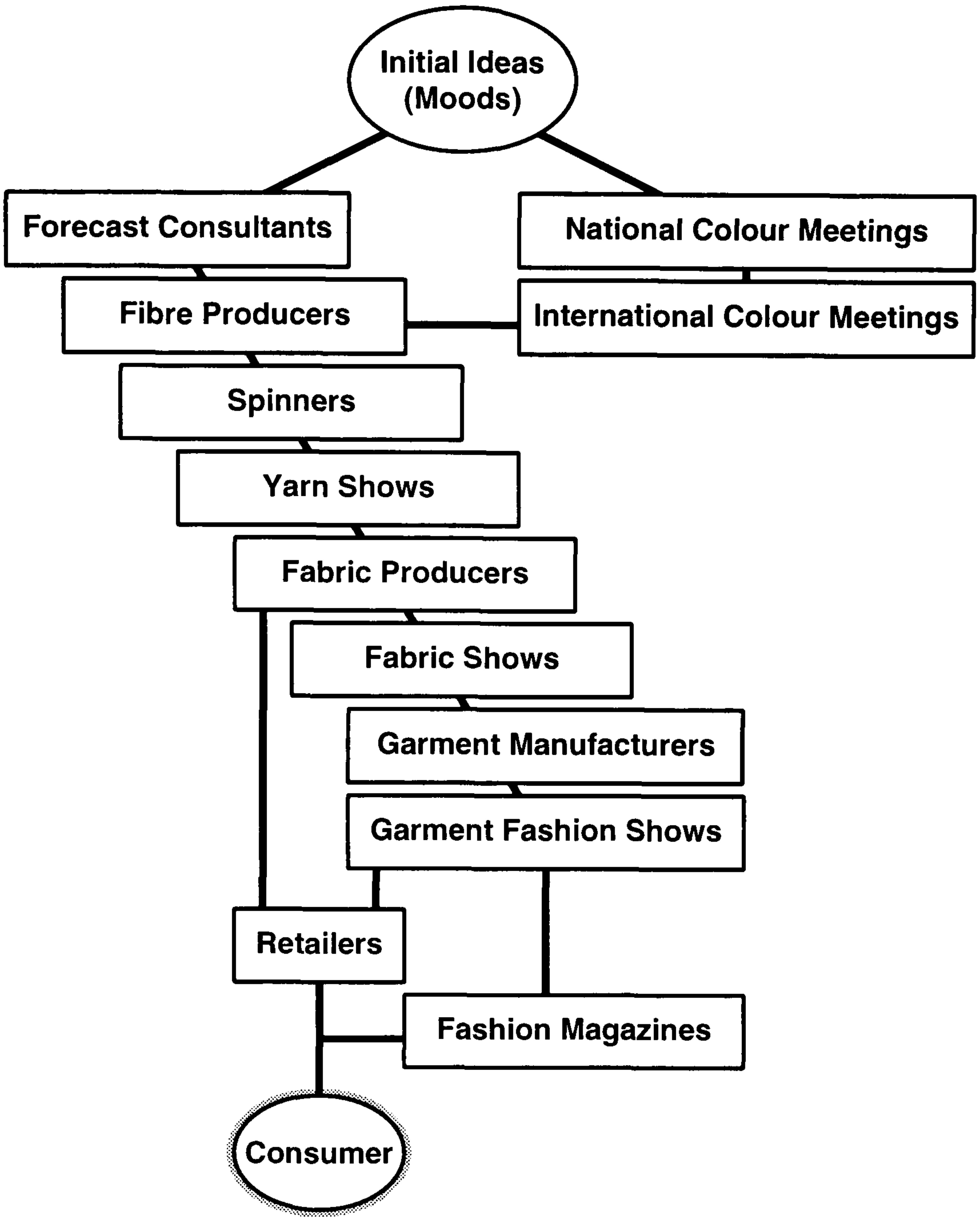
Typically, design begins some fourteen to sixteen months in advance of the season's final garment fashion shows. At this early stage, various colour ideas are explored — the intention being to make predictions as to the likely colour trends for the particular season — in order to provide essential guidance for the later stages of design. The *British Textile Colour Group* (BTCG) plays a key part in colour prediction. This is an informal forum for colourists to meet and discuss their ideas and to judge the extent of consensus over colour trends. Four meetings are held each year and two of these are directly concerned with colour palette design. At these meetings, each group member formulates their own palette and these are subsequently amalgamated into a single palette which is used to represent the UK at *Intercolor*, an international group formed of representatives from twenty-five countries. Similarly, the Intercolor meeting also produces its own international colour palette for each season based on the palettes supplied by each group member. The BTCG palette is required to be *sourceable* (e.g. specified using yarn references that can easily be obtained) to ensure that it may be communicable.

The final output from both the BTCG and Intercolour is *not* regarded as being definitive; national preferences and differences of opinion dictate that the results are, in general, only used for guidance. The real value of these to the individual designer is in assessing trends and for confirming (or contradicting) their own initial ideas. These initial ideas can come from a variety of sources, such as books, image archives, interior design or past fabric trends. However, much of the palette production process would seem to be designer-specific. Another possibility is that the colourist may be constrained by the requirements of a particular customer's organisation: this will also impact on the design methodology. In any case, both BTCG and Intercolor have some degree of influence on the palette design process. An illustration of the flow of trends and design ideas is given in Figure 3.1.

Returning to the chosen example of the spring-summer 1992 season, work begins at around June 1990 and the palette may be decided upon by as soon as October 1990 — typically some four to six months after the formulation of initial ideas. (See Figure 3.2.) Then, from October to January/February, various storyboards are produced to illustrate how the palette would appear together with fabric predictions. Mood boards are also used to suggest a theme without any explicit reference to a particular garment form. These are shown to the palette designers' clients (who are, in this case, the apparel designers) so as to give an advance input into the actual fashion design process.

Alternatively, it may be appropriate to develop both palette, form and fabric ideas in collaboration

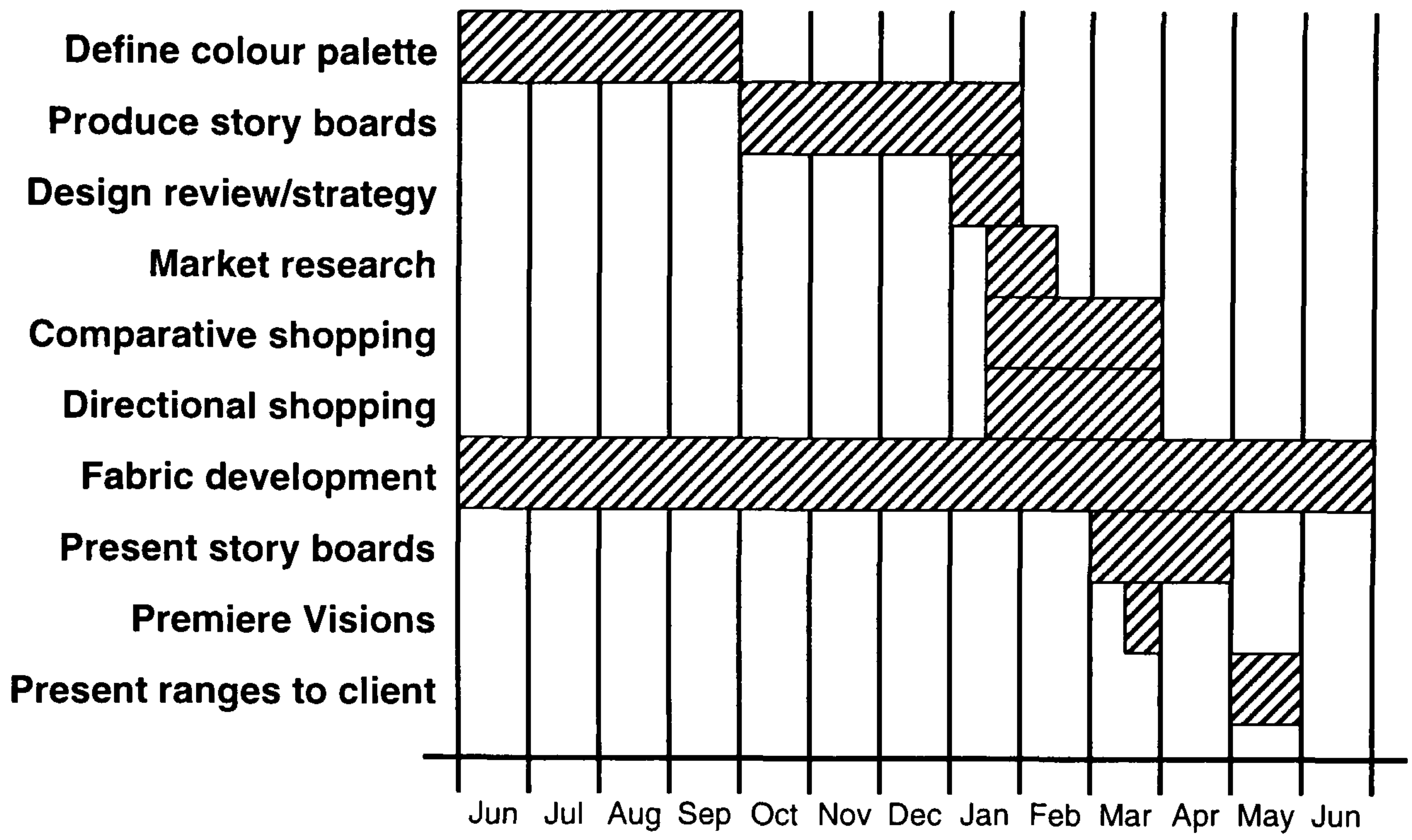
Figure 3.1: How ideas and trends are built up



with departmental buyers. In such cases, the palette may be used as part of the presentations made to potential garment suppliers towards the end of January (i.e. eight months after work begins).

A key point to note is that the palette selection process is carried out without any particular consideration of either specific garment form, fabric types or fabric designs. That is not to say that the colour palette designer does not take these into account, but rather there appears not to be a need to create visualisations to show how these colours could actually be used. It is possible that there may be practical difficulties involved with this, however it would seem more likely that fabric design and product form visualisation place too many constraints on the palette designer and might lead to the selection of a colour which *only* works well for one particular design or fabric. It can, therefore, be concluded that the process is principally

Figure 3.2: Design Activities for the Spring/Summer Season



one of choosing and organising colour patches with the proviso that the palette itself must be flexible enough to look good in a range of materials and designs.

The final output of palette design is a set of physical samples and these are fed into the garment design process, together with fabric ideas. Garment design begins typically one month prior to first seeing palette ideas and the first task is to review what has been successful (or otherwise) during the previous year. After this review, a number of concurrent processes are conducted to judge the market situation: *market research*, *comparative shopping* and *directional shopping*. Market research is aimed at establishing whether there is likely to be a demand for a new product idea that the designers wish to be developed. Where the product already exists, comparative shopping is used to evaluate the competitors' comparable products. Factors such as quality and pricing are considered and comparisons are usually made of high street goods currently on sale (i.e. one year before the target season). Directional shopping is less parochial and concerns *haute couture*: it involves visits to various avant-garde or designer label boutiques, fashion shows, etc. in selected countries. There, ideas from current "high fashion" are abstracted (sketch reports are made) and considered for use in "popular fashion."

In parallel with this "shopping," fabric ideas are developed. This usually involves several visits to different fabric mills (who may even arrange special shows to preview their forthcoming fabric ranges).

The directional shopping reports (showing shape and styling innovations), together with the designers' own ideas, are used as the basis for sketches of ranges. These are presented in the form of storyboards to potential customers. The storyboards consist of drawings depicting style alternatives, swatches of fabric and colour ideas. At this time, initial patterns and *toiles* (model garments or mock-ups) are produced to preview certain designs and assist with their costing.

An influential event involved in the finalisation of designs (and also for providing input into next season's work) is the international fabric trade fair, *Première Visions*, held biennially in Paris. At this fair, and also following it, fabric will be selected. Range presentation using the storyboard format is essential for buying. The retail buyers choose directly from these which particular designs they would like to see developed further into sample garments, presented at fashion shows and then ultimately leading to orders. Thus the purpose of storyboard presentation is to sell design concepts. The process of garment design is carried out over a very short period — approximately five months — and the flow of information that takes place between each of the sub-processes is illustrated in Appendix A, Figure A-1.

3.2.2 Colour Specification, Control and Communication

Colour Palette Design

During the initial stages of this design process, colour specification is crucial. Colour ideas are developed and presented in palette format using any readily available physical samples. It is not uncommon for different substrates (such as paper, wool and different types of yarn or fabric) to be used together in one palette, particularly during the early stages of its production. When ideas are being discussed at the BTCG and Intercolor meetings, colour communication between each of the members becomes important. The BTCG promotes the use of sourceable samples (in the form of thread or yarn), however, there is no "standard" layout for colour palettes. Furthermore, some colourists will purposely construct their palettes using different substrates in order to reflect directions in fabric types. (For example, there might be a trend for silky looking shirts and this could be reflected by the selection of silky substrates for shirt colours.)

Producing a palette is not merely a matter of finding which shades work well together; for example, the designer must also consider fabric and garment type that the palette colours are likely to be applied to.

In the initial stages of palette design, the relationship between colour appearance and fabric seems to have some significance and it may not be acceptable to use paper samples at this stage (i.e. designers actually *prefer* to see fabric and yarn samples). It would seem that the use of recognised colour order systems to support colour selection is quite rare: occasionally they are used as source material for constructing the early palettes. Thus, colourists may be constrained in their choice of colours by the compromises that have to be made in locating suitable physical samples. Irrespective of the means of colour selection, ultimately it is required to produce physical samples for communication between palette and garment designers.

A paper copy of the palette is sometimes used to communicate early palette designs; the colours here are only used as a guide since the later fabric palettes may be significantly different. (Either due to colour reproduction, change of substrate or simply because new colour ideas have been developed during the finalisation of the palette.) Once the palette has been finalised, it needs to be disseminated: many copies are often required and these are usually produced by attaching thread or fabric samples to a card (the same substrate is used for all the palette copies). Some compromises necessarily have to be made where samples cannot be located that exactly match the original (multi-substrate) palette. Differences in palette background, size, substrate and viewing conditions can cause colours not to be perceived as intended when palettes are communicated. Standardisation of palette format may be useful to improve the fidelity of colour communication however, as already mentioned, different substrates are sometimes deliberately used for effect by the palette designers to indicate fabric trends.

Garment Design

Colour and form are treated as distinct entities for much of the early stages of garment design. Many fabric or form ideas are created without reference to a specific palette. Indeed, colour is dealt with as a "concept" rather than as any more tangible representation. Colour precision only begins to become important once the designers are preparing the storyboards to present their design ranges to clients. The storyboards each have their own theme (e.g. "floral") and have reference to specific garments which are related by the theme. As these boards are used to sell designs (this being the first stage in the buying process), colour fidelity is critical to the success of this work.

Within each storyboard, three main components of the design concept are presented: fabric type, design form and colour. This might include fabric swatches (fabric suggestions), black and white line art or sketches of shapes (depicting form) and separately illustrated colourways. From these individual parts, the buyer must put together a mental picture of the final design. This is a difficult task and there is much uncertainty which often leads to a lot of redesign work needing to be carried out during the period between selection from sketches and the final fashion show presentation to the client. It is quite possible that the final goods will appear different from the buyer's own expectations, hence changes are required. To combat this problem, greater realism in design presentation is highly desirable. Most of this uncertainty can be removed by showing the actual colours (whether specified externally by the client or internally by the designer) on the correct fabric type using the desired shape and size. This includes matching the storyboards with any external references (such as the client's palette and, ultimately, the completed garments).

3.3 USE OF COMPUTER AIDED DESIGN

At each of the garment design sites visited, CAD systems were being used extensively for a number of tasks including both actual design work and also in support of design presentation. However in all cases, low colour fidelity was a major problem which had to be dealt with at each stage of colour communication (i.e. between palette, screen and hardcopy). Difficulties normally begin once the palette is received and is subsequently entered into the CAD system. Because fidelity between screen and printed output is so poor, it is typical to match directly to this output and completely *ignore* the appearance of screen colours. Various techniques have been developed by the designers/operators for obtaining the desired hardcopy colours. These typically involve the output of several printed "atlas" pages (i.e. showing various combinations of the printing primaries) for each device. Then, to match a palette colour (or any other physical sample), a close match is located within the pages of this atlas and the original reference used to produce it is entered into the CAD system. This process is frequently time-consuming and is fraught with additional problems (such as the stability of the inks and the difficulty in locating intermediate colours).

Acceptance of CAD for textile fashion design is not yet wholesale: not all the design groups studied used this technology for actual garment design (as opposed to finishing or presentation). In some cases, this is because they buy in external fabric designs (i.e. they concentrate on selecting rather than designing fabric), however it is still possible that some redesign may be required although the scale of this work is much smaller (and hence involves less CAD). Where extensive fabric design work is done, it was found that the exact role played by CAD systems varied considerably.

At one of the design sites visited, the CAD system was only being used for the final stages of fabric design. There, the design of the basic form was accomplished using conventional media. A number of reasons were given for this. Firstly, it was felt that where the work involved relatively small design jobs, it was more productive to have these undertaken by the CAD operators rather than tie up key designers (who could be left to more important work). It was held that design using conventional media (such as paper and pen) was often much faster and that this encouraged greater thought and creativity in the designer. CAD systems, it was argued, made it all too easy to abandon past experience and instead rely on trying out many small adjustments to achieve a result. Another justification was that the CAD operator was often in high demand for fabric design entry and colouring, thus limiting the availability of the computer system.

At other sites, where the designers had been trained to use the available CAD technology, they generally chose to design directly at the computer. There, the system was used to good effect for such tasks as recolouring existing designs (which were first scanned in). This type of operation was more suited to a broader client base which demand a greater variety of design work.

In summary, the principal uses of CAD were found to be in both design and presentation (via storyboard or mock-ups). Some of the tasks to which it was put to use included:

Design:

- Producing simple designs such as spots or stripes. Alternatively, CAD can also enable a greater amount of intricacy in design.
- Performing repetition of a basic design.
- Recolouring artwork or fabric designs (which are usually scanned electronically into the system).
- Editing existing fabric designs.

- Generating text, labels and other graphics.

Presentation:

- Printing designs to scale and in the shape of the final garment.
- Printing coloured swatches.
- Generating fabric designs to be transferred onto actual garment mock-ups.
- Producing label and packaging designs to complete the overall design concept. (This is of particular relevance where the garment is to be shown to the customer in package form, e.g. socks, tights or boxer shorts.)

Future use of CAD might also include the store layout of a product range. At present, the main benefit of CAD is the greater level of realism that can be achieved at a faster rate and at a lower cost than by conventional (manual) methods. Greater realism and a faster response are both likely to promote sales.

3.4 SUMMARY OF FINDINGS

Much of textile fashion design is geared around two main seasons and work for these is done well in advance of the current season. Because designers are working ahead of the current period, it is vital that accurate forecasts be made of future market trends. Colour information is communicated between forecaster (colourist), client and garment designer in the form of palettes. It is usual for palette design to proceed without specific regard to fabric type or garment form. Some garment design is also performed without reference to a particular palette (colour and form are separated). In order to sell their designs, the garment designers produce storyboards to illustrate design concepts to their clients. Specifically, these storyboards depict fabric type, design form and colour.

There are two particular stages of the palette design process during which colour appearance is critical to the designer. During this work, subtle judgements need to be made requiring a close match between imagined and physical colours. Secondly, there has to be a close correspondence with the designed palette and that which is finally communicated. As far as the garment designer is concerned, colour fidelity concern is focused on story board production. Story board colours are required to match either in-house or customer supplied palettes. The higher the degree of resemblance of the story board to the actual garments, the less the likelihood of disputes between garment manufacturer and retailer (and hence less chance of having to redesign).

At present, CAD is used by garment designers primarily as a tool to support their design presentations to clients. In some cases, CAD is also being used for design itself, however its usage is by no means uniform throughout the industry. Factors such as client base, group structure, design responsibility and innovation seem to play a part in determining exactly what is done. Colour communication fidelity between different media is regarded as being poor and this tends to limit the effectiveness of such systems. Because of this difficulty, it is common practice to ignore screen colours and instead concentrate on the appearance of printed output. This can lead to misjudgements over the use of colour within designs and diminishes user confidence.

Colour accuracy is important in textile garment design for a number of reasons. For corporate fashion, there is often a requirement to match company colours. Elsewhere, fashion trends (including colour) dictate what is sold. Designers are often required to match their client's palette; this is particularly important if different garments (which may be produced by other design companies) are to match each other in store. Consequently, designs are more likely to be sold to clients if the designs/colours match the buyer's expectations. Greater realism for design presentation is highly desirable so as to lessen the buyer's uncertainty over the design's ultimate appearance.

The communication of colour is equally vital. Prior to actual garment design, the primary medium used is the colour palette. Printed samples, fabric or yarn may also be exchanged at various stages. At some point in time, it is required to produce fabric in the desired colours and to do this, typically involves communication with an external dye house. In addition to transferring colour information to the dyers, some limit on the allowable colour variation must be specified. Each instance of colour communication leads to the possibility of error or loss in fidelity.

3.5 RECOMMENDATIONS

The specification, reproduction and communication of colour are both important and problematic issues for workers in the area of textile design. While current CAD systems are used by garment designers to assist with certain design tasks, in general, they do not address colour fidelity. Furthermore, the requirements for CAD are non-uniform across the garment design industry thus making it difficult to develop a comprehensive solution. A more realistic approach would be to augment existing CAD systems with a number of "appropriate" colour management tools. This idea was suggested to a number of designers and a list of their common requirements in this area was compiled and is given below.

(a) **Colour selection** — allowing the location and adjustment of arbitrary colour shades. For ease of use, these should be presented as a systematic arrangement of colours (e.g. using one or more popular colour order systems).

(b) **Palette creation** — the ability to construct on-screen palettes. This includes grouping and re-ordering of colours in an arrangement similar to that used for physical palettes. As already demonstrated, the colour palette concept is very important to textile designers.

(c) **Colour visualisation** — colour appearance is dependent upon the context in which it is viewed. Therefore, it is vital to be able to be able to preview colours under a variety of viewing conditions including: different backgrounds (including the overlap of selected colours), light sources (e.g. daylight or tungsten lighting) or textures.

(d) **Colour adjustment** — the modification of shades either individually or collectively (e.g. making a group of colours darker) is particularly useful for creating new shades from existing palette colours.

(e) **Colour output** — producing paper samples of colour shades, palettes or designs is an essential part of the colour communication process. Output could include (paper) colour hardcopy or a link to a recipe prediction system (to enable dyed samples to be made).

(f) **Colour input** — the facility to "scan" physical samples and possibly re-work them on the screen is another possibility for colour entry.

(g) **Colour storage** — the ability to save work and to build up databases of past work (including names, recipes, customers, etc.) or competitors' shades is a required element of any practical system.

(h) **Colour communication and quality control** — colour communication occurs during many stages of the garment design process: both internally and externally to each of the design groups. Most colour reproduction processes are less than perfect and so when colour is communicated (e.g. from designers to dye house), some measure of the desired precision should also be specified.

Throughout, a high degree of colour fidelity is desirable, as is a close correspondence at all times between screen and output. Using an electronic colour representation for (h) can help to improve fidelity and also to save time. (It is quicker to transmit this information than to deliver physical samples, which would, in any case, have to be located or produced prior to sending.) Although currently not widely used by textile designers, the use of various popular colour notation systems would seem appropriate for requirement (a) as these are used in other industries for similar tasks.

The appearance of the palette specified in (b) is important: it was found that the arrangement (i.e. size and spacing) of colours within a palette affect its perceived "mood." Also when adjusting colours (d), the designers thought that it would be useful to view the original colours alongside their adjusted counterparts as reference in order to judge the changes that have been made. Therefore, a separate area (distinct from the main palette area) is required.

3.6 CONCLUSIONS

In this chapter, a review of the processes involved in the textile garment design industry was given. This was seen to be centred around the creation and subsequent usage in fabric design of seasonal colour palettes. In studying the designers' use of colour, it was found that the key problem that they face is the lack of fidelity (particularly across different media and when colour is communicated). The application of CAD was found not to be uniform across the design industry, however a set of common requirements were established which could be used to improve the colour performance of existing CAD systems. Although certain requirements (such as palette creation) are task-specific, the problems of colour fidelity, specification and communication are equally relevant beyond just this domain. It is also likely that any solution to these will also be of general use to other areas where colour plays an important role.

Chapter Four
Current Approaches

CHAPTER FOUR: CURRENT APPROACHES

4.1 INTRODUCTION

In the early days of DTP, what was seen on the screen inevitably bore almost no resemblance to what was eventually printed out on paper. This problem has since been solved for type and typograpy, but colour still remains an elusive problem. For many users of computer systems, this presents only a mild irritation; it does not stop their systems from being useful. Some users, however, do find this highly limiting particularly where the precise appearance of a single colour can determine the success (or otherwise) of their work. Such users include amongst their number graphic designers and, as mentioned in the last chapter, fashion designers. As was seen, colour fidelity becomes a problem at each stage of colour communication and, in particular, where this involves a change in media. Also lacking (or severely limited) was a consistent and accurate way for users to select and specify their colours.

This chapter presents a literature survey of current approaches and limitations to achieving colour fidelity, specifically focusing on computer-based design systems. The reproduction of a number of different colour order systems (as an aid to colour selection and communication) is covered, as is the interrelation of a number of such systems. A number of commercially available systems for colour management and "high-fidelity" design are examined with a view to gaining an appreciation of the current state of the art. Exact CAD requirements are non-uniform and, as will be seen, there are few (if any) truly complete solutions to users' problems. Several partial solutions do exist, however, which concentrate on particular aspects of colour in CAD.

4.2 COLOUR FIDELITY AND COMMUNICATION

Introduction

What you see is what you get (or WYSIWYG — pronounced "whizzy-wig") has, of late, become a popular and desirable quality in modern interactive systems. It is a term most commonly applied to the graphical and typographical elements of document creation, however there is an increasing demand for the same high degree of correspondence to be so for colour. By and large, font problems have been solved and what you see on the screen *does* closely resemble the final printed output. The same, however, cannot be said for colour at the present time. This section takes a look at current approaches to solving the problems of fidelity and communication which are the principal obstacles to achieving the goal of WYSIWYG colour. Before proceeding, it is worth taking a brief respite to see exactly what the implications of WYSIWYG are.

In [Thim90a], some of the consequences of hidden information (or *modes*) in interactive systems are described. It is argued that users tend to assume that what cannot be seen at the user interface does not exist and, conversely, what is seen does exist. Ignoring tense,† this leads to two possible interpretations of WYSIWYG:-

(i) What the user can see (i.e. information that is transferred from computer to user) is what the user gets (i.e. the information output from the computer as a result). This has the consequence that the user is always working with the finished article.

(ii) According to the legal maxim, "*De non apparentibus et de non existentibus eadem est ratio*" ("what does not appear is presumed not to exist"). Thus, if you can't see it on the screen, you can't do it!

The first of these interpretations agrees with most users' expectations of WYSIWYG. The second interpretation clearly constrains the usefulness of any WYSIWYG system. (For example, many WYSIWYG word-processing systems curtail the precise control an expert user may wish to have over a document's formatting.) Having said that, WYSIWYG systems do have a number of advantages: they are more comprehensible as nothing is hidden from the user, they are more predictable and inspire greater user confidence in their operation.

4.2.1 Colour Fidelity

The benefits of using *colorimetry* to improve colour reproduction have long been recognised in a number of application areas including broadcast television [Spro83a], photography [Yule38a, Yule67a] and printing

† It is also pointed out that WYSIWYG has a tense: what you *will* get versus what you *have* got (inside the computer).

[Ston88a]. (See also Hunt's *objectives in colour reproduction* in [Hunt87a] — which was also mentioned in §2.7.3 — for further background on this topic.) Although colorimetry has been used successfully to solve many fidelity problems, significant differences due to dissimilar viewing conditions have still to be surmounted. A number of approaches have been put forward to attempt to compensate for these differences and these are now described.

The white point of a viewing field plays a critical role in the perception of colours. Our visual system "compensates" to some degree for different white points (and colour temperatures): a process known as *chromatic adaptation* (covered in §2.5). However, this is only the case where an observer has had time to adapt to the particular viewing environment. Similarly, the apparent brightness of a scene is dependent on the observer's adaptation. For example, when emerging from a darkened auditorium on a sunny day, the outside world can seem extremely bright for the first few seconds. There are a number of standard (or *de facto* standard) light sources in everyday use by industry. Amongst others, these include D32 to D34 for home movies, D50 for the graphic arts, D55 for daylight film and D65 (PAL) or Illuminant C (NTSC) for colour television. Each of these lead to a different white point and it is often desirable to be able to exchange colorimetric data between these dissimilar conditions.

One method commonly used to adjust for differences in white point is the *white-point transformation* (introduced in §2.5). The general use of white-point transforms is as part of colour reproduction processes involving the exchange of colorimetric data. In [Buck92a], the authors investigate the performance of such transforms for colour copying systems. Here, the same viewing conditions are used for both source and duplicate image (in particular, both media are surface prints) except that each is illuminated with a *different* light source and hence they have dissimilar white points. The objective is that when the copy is compared side by side with the original under the same conditions, the two should yield identical tristimulus values. A number of different interchange spaces† (including RGB, YES [Xero88a], CIELAB and CIELUV) were compared and it was concluded that using RGB type coordinates yielded closer tristimulus values than either CIELAB or CIELUV. The paper also states that the method used of keeping the RGB values for

† The *interchange space* consists of intermediate colour values (ABC) which are used in transforming between the source and destination device independent representation (XYZ), i.e. $X_1Y_1Z_1 \rightarrow ABC \rightarrow X_2Y_2Z_2$. Each set of XYZ corresponds to different white point.

white constant for different white points is actually equivalent to the von Kries adaptation formula (see §2.5) which is part of the Hunt colour appearance model. However, this is not generally the case as Hunt's model also considers differences in media which were not studied here. Furthermore, the white-point transform only takes account of illuminant and substrate (for surface colours in this case) to produce a colorimetric (tristimulus) match. This does not necessarily mean that the source and copy will be *perceived* as being the same.

In [Bern92a], it is proposed that *device independency* and *viewing condition independency* are both essential components in realising faithful colour reproduction. Conditions must be identical for colorimetry to be applicable. (The necessary conditions for attaining a colorimetric match were discussed in Chapter 2, §2.3.5.) It is argued that for accurate matching between screen and hardcopy, both images must have identical white points and luminance levels (in addition to further constraints). These restrictions are regarded as being impractical for most applications for a number of reasons including the difficulty in changing a monitor's white point, the use of dissimilar surrounds or textures and also because of differing colour gamut limitations.

Berns then continues to discuss how colour appearance modelling can be used to achieve viewing condition independency and how this is then used to transform colour images from one set of viewing conditions to another. To this end, a five-transform "colour WYSIWYG flowchart" is given which is very similar to the four-stage transform given in [Yous91a] (and covered later in §5.3.1.2). The first and last steps involve conversion between device dependent and device independent colour (XYZ) via device colorimetric characterisation. Two further steps convert between the device independent and viewing condition independent (colour appearance) representation. A number of appropriate colour appearance models were suggested. Finally, an inner transform is given to enable a number of image processing operations. Suggested transformations that could be performed in colour appearance (viewing condition independent) space include gamut mapping and compression.

The paper goes on to give a description of how the five-transform process was verified experimentally. This experiment used six images: all photographic reflection prints which were digitised using a colorimetrically characterised scanner. Each was then processed separately using either XYZ (to achieve device independency), CIELAB (to additionally account for the surround and white point) or the Fairchild [Fair91a] chromatic adaptation model (which also contends with differences in white points and incomplete adaptation). The resulting images — three per original image — were then displayed on a computer screen and assessed by a panel of observers as to which of the three models performed the best in terms of their reproduction of the source image shown, for comparison, in an adjacent viewing booth. A number of light sources were used in the viewing booth, while the monitor's white point was set to approximate D65. Both images were viewed against similar dark surrounds and were of the same physical size. Two light sources were used to view the source images.

After scanning the source image, an empirical model was used to convert the input RGB to tristimulus values. Two such models were used: one for each light source. The experimental results showed that most observers preferred those images processed using either CIELAB or the Fairchild model, i.e. tristimulus values alone were not sufficient for achieving acceptable colour reproduction. The paper concludes that without sufficient knowledge of conditions (such as device media and calibration, instrument geometry and viewing environment), device independency can create more problems than it solves due to ambiguity.

So far in this section, we have seen how perceived colour fidelity can be achieved across non-identical viewing conditions through device and viewing condition independency. Next, we take a look at how this theory is applied to complete systems by examining in detail several existing architectures for colour management.

4.2.2 Colour Management Systems

Recently, there has been an explosive growth in the area of colour management with many companies in the field of desktop publishing (DTP) vying for some sort of technical advantage in what is a highly competitive market. The application of colour management systems (CMS) outside of DTP is much more limited, however. In this section, a number of systems are described, although since the majority are proprietary (and therefore unpublished), what information there is available concerning these is of the "sales brochure" variety thus making an objective assessment difficult. In spite of this, looking at the features provided by such systems is useful in its own right.

First, a definition of exactly what is meant by colour management is required. According to one definition [Walk93a], a colour management system is a collection of software and data which may be used by applications in order to achieve improved cross-device colour rendering. Hence, a key goal is to provide the means for the management of colour including its specification, communication and reproduction across an heterogeneous environment. It is also important to provide *consistent* colour, regardless of the device being used to reproduce it. A more narrow definition of a CMS is given in [MacD93a], which considers only the management and communication aspects of colour systems and focuses on the task of getting coloured images from one device to another through a series of image transformations (relying on properly characterised devices). Colour management can also mean slightly different things to different people. In the case of dyers [Thor94a], for example, the key area of concern is the accurate, repeatable dying of fabric either first time or corrected after feedback. Hence, the precise management and control of the coloration process is paramount, with other diverse areas such as quality control, production monitoring, dyestuff stock control, match prediction and dye recipe formulation (with control over cost, colour fastness and metamerism) also being considered. Here, a broader view is taken and some of the more general characteristics of a CMS (though not all of these may always be provided) are given as follows:-

- Fast/accurate colour matching between any two devices. The most common application of this is to convert colours between display and printer devices when producing a hardcopy of a screen document. This usually involves "device calibration profiles" or DCP which provide a means of relating device coordinates with those of some other device independent colour specification. Also, it often involves some sort of gamut mapping and/or gamut compression.
- Simulating on the screen what output would appear like if it were to be printed on a particular device (known as *soft proofing* or *previsualisation*).
- Colour selection with the handling of out of gamut colours and the relation of colours to a reference colour space (i.e. device independent colour specification).
- Device-independent interchange of images. Colour representation needs to be *objective* (that is, relate to CIE standards), not require excessive storage and also yield good interactive performance.

Ideally, these should all operate transparently with existing software and hence would probably need to be incorporated into the computer's operating system.

Colour management technology, it is proposed in [Murc92a], takes elements from three main disciplines: colour science, device transforms and human interface design. In this scheme, colour science supplies the colour interchange spaces (such as the CIE XYZ system) which, together with suitable device transforms, enable device independent colour reproduction across different media. (It is also argued that such spaces must model certain aspects of the human visual system.) The human interface plays a key role in the success of any CMS; how colour management is presented to the user directly influences the system's effectiveness. Finally, it argued that standardisation within each of the three disciplines mentioned is going to be necessary for colour management to be practicable. In particular, this includes adopting standards throughout industry for colour interchange spaces and device transforms.

One existing problem with many current CMS software is that each system defines its own format for DCPs (but see the discussion of InterColor later on). Thus, any device manufacturer must supply a number of such profiles for each CMS to operate on. Also, regular calibration (e.g. to compensate for drift or media change) is necessary with the result of this recalibration being appended to the relevant DCP. One notable feature missing from many systems for colour management is the ability to communicate colours or colour images (as opposed to just printing them); this topic will be covered in the next section. What follows next is a brief description of current CMS technology.

TekColor

One of the first systems, TekColor [Tekt90a, Tekt90b], was launched in 1989 by Tektronix with the hope of becoming an industry standard. It runs on Apple Macintosh personal computers and is currently bundled with Tektronix colour printers and some other third party scanner and monitor calibration software. TekColor is composed of three main parts:-

- *Device characterisation* in the form of per-device colorimetric information in order to achieve device independent colour.

- *Colour matching* employs the device characterisation data as part of a gamut mapping process between devices. Part of this process may also involve managing mismatches where colours in the target device's gamut do not completely accommodate the whole of that of the source image.
- *Colour selection* is supported via a graphical user interface to whichever colour model is used. (These could typically include the perceptually based TekHVC colour space or the default colour wheel provided on the Apple Macintosh.)

The main task carried out by TekColor is to solve colour fidelity problems between the various colour devices being used. A key aspect of this is that the user can apply colour without regard to the actual device that will later reproduce it. Additionally, the user interface allows the user to visualise the extent of both screen and printer gamuts (represented as "hue leaves") — thereby assisting the user to choose *only* those colours which can be reproduced by both devices, if that is what is desired.

Colour matching can be performed by TekColor in one of two ways: either *exact* matching (yielding a close resemblance to screen colours) or *white adjust* (where colours are "rebalanced" to compensate for differences in monitor and paper white). Without the use of a colour appearance model, however, the success of this method is likely to be limited: the human visual system is considerably more complex. The exact viewing conditions for a match are *not* defined; rather screen and printed output are simply claimed to appear *close* under average (non-extreme) conditions. Other discrepancies are likely to occur if a particular printer or monitor differs from TekColor's role model for that device (e.g. due to manufacturing differences or changes in printing inks or as a result of printing onto different substrates). While it is possible to update the device calibration files to take such differences into account, doing this is not part of the basic TekColor system.

ColorSync

ColorSync is the name of Apple Computer's own colour matching architecture for its Macintosh range of personal computers. According to Gerry Murch, Apple's director of imaging software [McMi92a], ColorSync provides a common *framework* for colour management and the colour matching that is provided is meant to be a minimal default which can be superseded by more advanced algorithms supplied by Kodak or EFI — see later. (In [Walk93a] the distinction between a colour management system and a colour management framework is pointed out. ColorSync is considered to fall under the latter category because it could be used to mediate a series of colour transforms involving more than one colour management system.) Other developers are urged to adopt Apple's API† and furthermore, its open architecture is meant to encourage third parties to add or customise the system with other more specialised matching models for greater speed or fidelity. As with other colour management systems, the principal goal is to support colour matching between source and destination devices. (Devices in this instance being scanners, monitors and printers.) ColorSync realises this goal by distributing the responsibility for matching amongst the device drivers (and developers of such software) rather than leaving this to each individual application. Therefore, ColorSync is able to operate transparently with the majority of existing application software. A further advantage is that additional devices can be handled without the need to update application software.

Internally, the system utilises CIE XYZ as a reference space for matching between different device spaces. Associated with each device are a number of *profiles* (e.g. in the case of a printer, a different profile may be necessary for each type of paper). These profiles include a description of the colour gamut together with a *colour matching method* (CMM). ColorSync provides only very basic system default profiles and CMMs,‡ so it is usually desirable to replace these with custom versions which are better able to model the colour characteristics of the specific devices being used. A number of colour matching options (such as "perceptual" or "colorimetric") are also available to modify the behaviour of each CMM. These effectively control how gamut mapping between devices is accomplished.

For those applications which are "ColorSync-aware," there are a number of further possibilities. By querying the device colour profiles, it is possible to provide more accurate print previews (simulations) on screen. The profile data also enables an application to discover which colours are inside or outside of a particular device's gamut. Finally, ColorSync makes it possible to tag pictures with colour profiles thus creating the potential for accurate colour communication of image data.

† API — application programming interface

‡ The default matching method uses screen RGB as a reference space.

Sun Microsystems

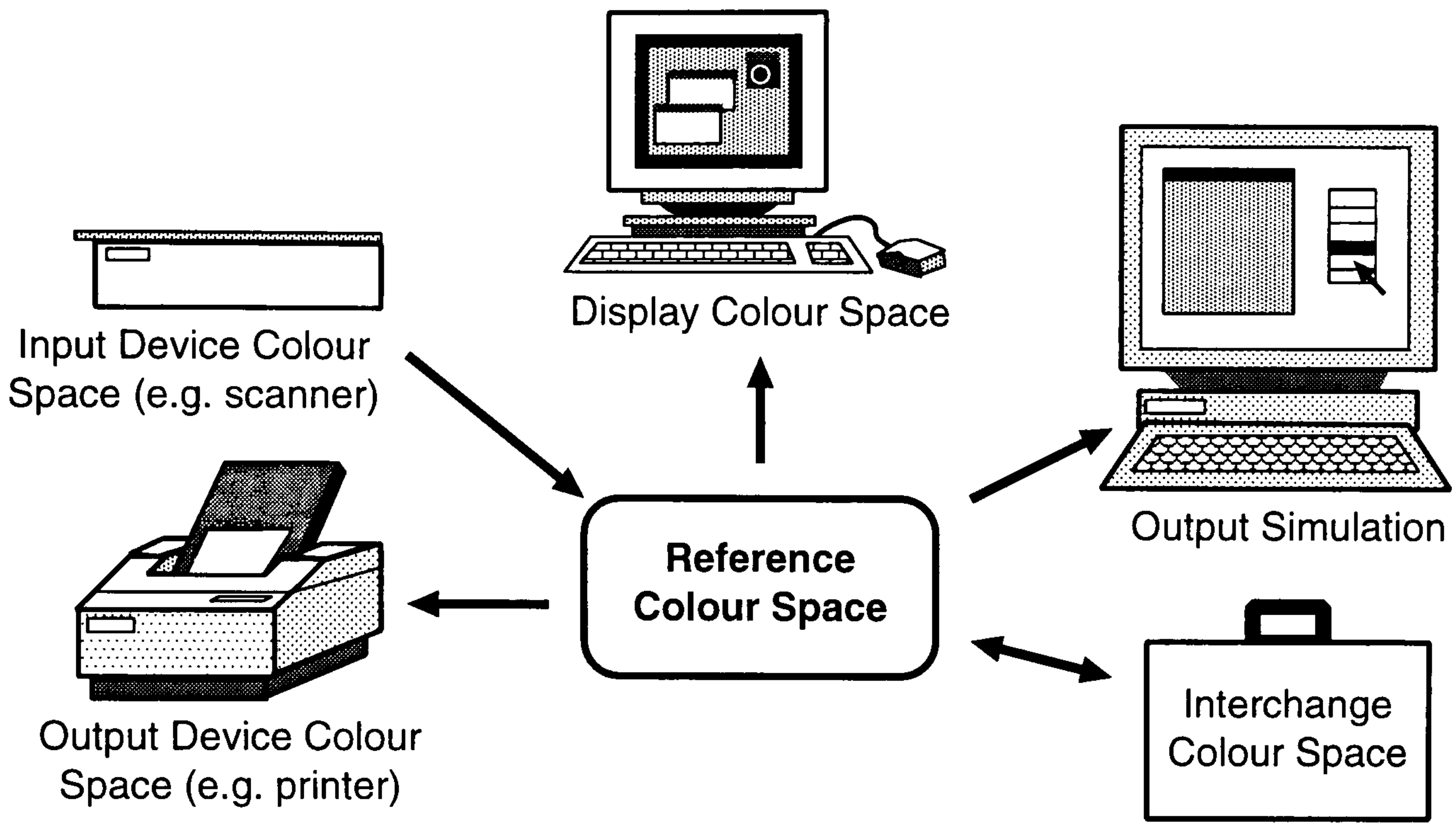
Sun are also planning [Poyn92a] to introduce CMS technology to their workstations. As with Apple's product, this also provides a framework for colour management by defining an API to various colour transformations. Each of these colour transformations (known as CMMs or colour management modules) handles transformations for a certain device class. Again, the architecture allows for the addition of third-party CMMs. Colour management is to be closely integrated into Sun's graphics libraries and it is claimed that this will allow it to operate with existing (unmodified) software.

Kodak Colour Management System

The Kodak Colour Management System (KCMS) [McMi92a], developed by Kodak Electronic Printing Systems is employed in their *Precision Colour Management System* (PCMS) [Blai92a]. This is targeted at the high-end market, such as professional imagesetters and service bureaux. PCMS is used as part of Kodak's Prophecy and PCS100 imaging workstations and is also sold (in the form of its "Precision Color Management" software) as part of other companies' systems such as RasterOps "CorrectColor" and Radius "Precision Color Matching System" both of whom also produce their own monitor calibration hardware. KCMS provides a series of "Precision Transforms" (or PTs) which are used to perform various colour manipulations (including gamut mapping and gamut compression) shown in Figure 4.1. Note that the reference colour space shown here is one defined by Kodak for the internal interchange of colour data. Because these transforms are computationally demanding, the process can optionally be accelerated through additional hardware in the form of Kodak's "Precision Colour Transform Engine." One particular aim of PCMS is *not* to let users select colours which cannot subsequently be printed — the system will prevent them from being chosen. (Thus the system is WYSIWYG in *both* of those senses mentioned earlier in the introduction.) Another limitation is that applications must be specially written to take advantage of the KCMS routines [Koda91a] which Kodak sells as part of its toolkit.

Kodak also provide a low-end solution (i.e. for desktop publishing) to the problem of colour management in the shape of *ColorSense*. This is built on top of Apple's *ColorSync* architecture and so, unlike PCMS, is able to work with the majority of existing application software. Functionality provided with the

Figure 4.1: Colour Transformations used by the KCMS



system includes calibration of monitors and scanners, colour modification and print output simulation.

EFI

The EfiColor Colour Management System [EFI93a, Barz93a] produced by Electronics for Imaging Inc., like Kodak's PCMS product, is also targeted at the high-end user. It is implemented within a client server architecture (applications are clients) and consists of three separate parts: the EfiColor API, processor (the server) and device profiles. The API is both hardware and system independent and consequently a developer's toolkit is available for a variety of computer platforms including Apple Macintosh, IBM PC and a number of UNIX-based systems. A subset of EfiColor's functions can be used through Apple's ColorSync. The EfiColor processor, typically running on separate hardware for optimal performance, carries out colour transformation services on behalf its clients for which it relies on the device profiles. These consist not only of colour characterisation data and gamut information but also include further device-specific detail (such as screen frequencies and angles) which may used to yield the "best" results on a particular printer. Colour profiles may be updated to reflect a device's current performance using the *Fiery Print Calibrator*. This consists of a densitometer which measures test prints output from a device and, on the basis of these measurements, makes corrections to the profile. (One unique feature of the system is its ability to visualise the extent of these corrections. This enables the user to detect if a printer's performance is significanly adrift from the norm which may be a sign of a malfunction.) Libraries of profile data are available for various colour devices and further "profiles" are available for various colour standards such as PANTONE, CIE XYZ and SWOP.†

One application of this CMS is the *Cachet Colour Editor*. Cachet includes a number of interesting features which are summarised below:-

- *gamut alarm* — in advance of printing, exactly which colours lie beyond the target device's gamut (and so cannot be accurately reproduced) are identified. On screen, this is represented by displaying the original image with each out of gamut pixel overlayed with a single distinct colour. This colour stands out from the rest of the image making it immediately obvious which areas of the picture are affected. An adjustable sensitivity control makes it possible to limit the colours identified in this way to only those which are significantly out of range. Out of gamut colours can be dealt with either by manually editing them or by having the system automatically choose the "best" in-gamut colours.
- *output simulation* — a print preview function enables the appearance of the final printed image to be simulated on the screen before actually committing it to paper. Alternatively, this can be used to preview the output of one printer on another printing device.
- *communication* — associated with each image data file is "metric colour" information. This is claimed to facilitate accurate colour communication and subsequent rendering. The metric colour data enables the accurate specification of colour.
- *colour editing* — Colour selection is principally via HLS (hue, lightness, saturation) and the PANTONE Matching System. Colour adjustment includes control of the following: colour "cast" (hue), saturation, lightness, exposure and tone. Adjustment can be applied selectively to areas of the original image and involves the use of several reference images. These illustrate the effects of varying degrees of change upon a picture. Similarly, this same process of multi-

† SWOP — Specifications for Web Offset Publications.

choice can be used in colour matching: successive colour adjustment is made with the screen image until a match is made with the printed reference. The system includes several such reference images for just this purpose with the aim being to achieve the "calibration" of a monitor to a particular viewing environment.

The system recognises and supports three different colour reproduction goals: *photographic reproduction*, using a proprietary gamut mapping algorithm which aims to achieve a "perceptually" match to the original; *colorimetric reproduction*, tries to reproduce the same colorimetric values (e.g. if a specific PANTONE colour was required); *presentation graphics* are a special case as it is frequently the case that very vivid colours are required (to attract attention) and these are likely to lie at the gamut limits for a particular device. Another point of note is that unlike Kodak's approach, the EFI system *does* permit users to work with colours which cannot be rendered. (It is argued [McMi92a] that "restricting the user to operate only within rendering colours is a guaranteed way to have less pleasing results.")

The X Color Management System

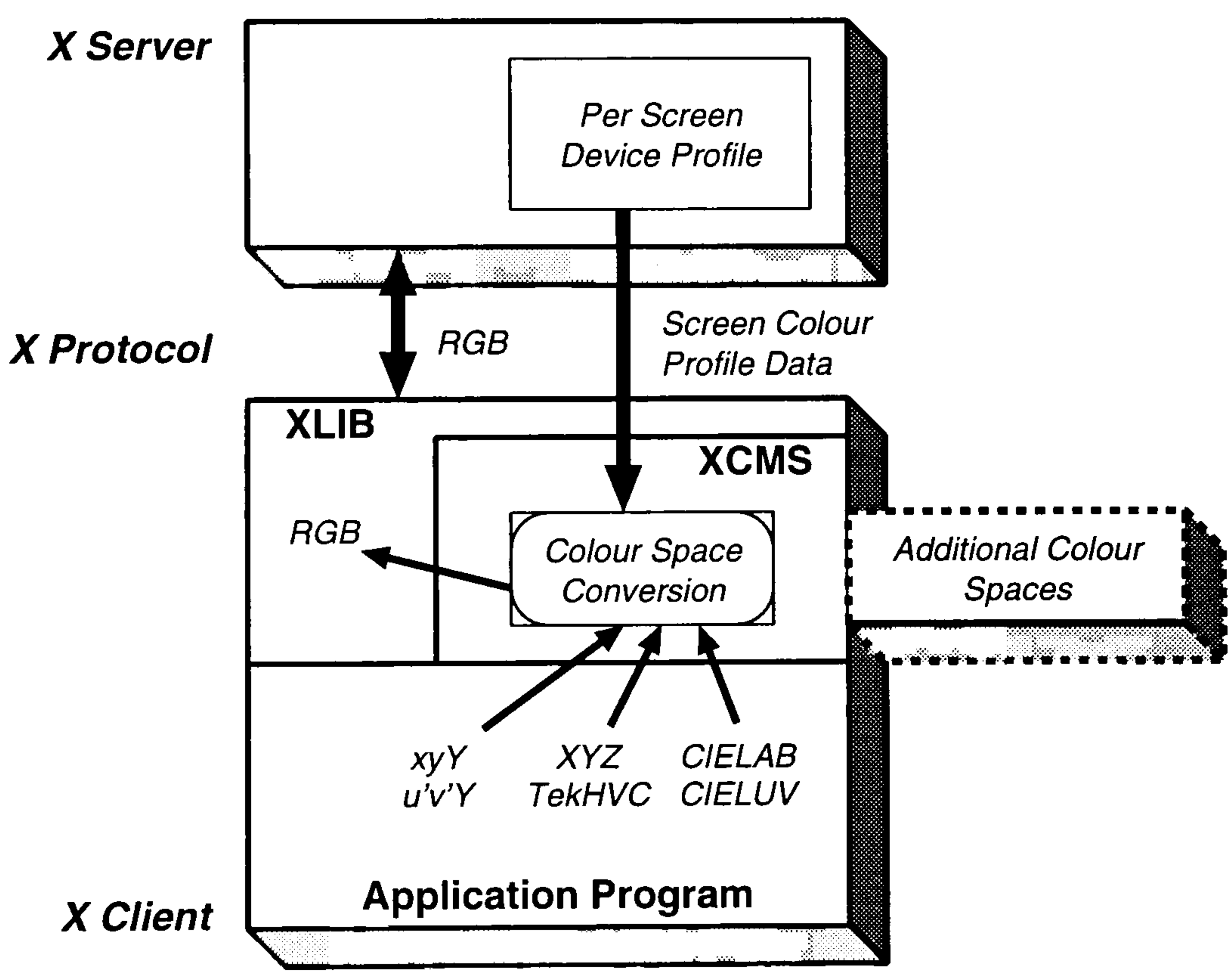
In contrast to the other systems mentioned here, this system is freely available from the X Consortium as part of their Release 5 of the X Window System [Sche86a]. There are a number of advantages to using the X Window System; one of the chief of these is that it provides a distributed and *open* windowing environment capable of operating on a wide range of heterogeneous computer platforms. X is fundamentally defined by the low-level X Protocol† and specifies colours in terms of 16-bit RGB values. Although the X Protocol does operate on a number of different types of display hardware (ranging from monochrome through greyscale and fixed palette-based to full 24-bit displays), there is no intrinsic support for device independent colour. Hence, in the X Colour Management System (Xcms) [Taba91a] it is necessary for each *client* to interconvert between some device independent colour space and a device specific RGB representation (which is what the *server* understands). Those colour spaces supported include: CIE XYZ, xyY, u'v'Y, CIELUV, CIELAB and TekHVC. Additionally, Xcms provides gamut mapping to cope with

† The X Protocol describes the format and semantics of the information passing between client applications and a server which manages the various input (e.g. keyboard or mouse) and output (usually bitmapped screen) devices. This is introduced in [Nye89a].

differences in white points (i.e. the application program's versus the output device's) and also the adjustment of out of gamut colours.

The Xcms API is included in the Xlib library [Nye90a] and this transparently manages the mapping to and from RGB device coordinates. The API is sufficiently flexible enough to allow the client application to trap and handle out of gamut colours (using gamut compression) or for those cases where there exists a difference in white points (white point adjustment). Thus, the open architecture makes it possible to either use the Xcms defaults for these cases or to supply user-defined colour matching routines. CIE XYZ is used as the basis for device independent (colour space) to device dependent (RGB) colour conversions. The device profile defining each screen's† characteristics (and used in converting between XYZ and screen RGB colours) is stored in the X server. This is in contrast to the rest of the Xcms which resides within each X client. (An overview of the Xcms architecture is depicted in Figure 4.2.)

Figure 4.2: Structure of the X Colour Management System



One application that uses Xcms is the *TekColor Editor* [Adam91a, Taba91a]. This supports the selection and manipulation of colours using the TekHVC colour space. The editor is able to "import" colours

† An X server can manage more than one screen at a time.

from other application programs (each may exist as a separate X client) and subsequently "export" the modified colours back to other applications. Note that this requires the cooperation of the X client concerned; colour changes are not enforced. It is envisiged by its authors that the use of the TekColor Editor will free software developers from the burden of producing a colour selection user interface within each application.

InterColor Profile Format

Very recently, a consortium comprising a number of vendors (specifically Adobe, Agfa, Apple, Kodak, Microsoft, SGI, Sun and Taligent) was formed with the aim of addressing the issue of cross-platform portability [Murc94a] under the auspices of the German publishing association, FOGRA. Their ultimate goal was to define an agreed profile format which could be adopted by all operating systems and colour imaging device developers. The resulting standard was based on that used by Apple's ColourSync CMS and known as the *InterColor* or the *International Color Consortium* (ICC) Profile Format [Anon94a, Greg94a]. This format describes the mechanism for transforming colour between the device dependent representation and a series of device independent colour spaces. The three categories of colour spaces recognised are:

- CIE-based (XYZ and CIELAB)
- RGB-based device dependent colour spaces (HLS, HSV, greyscale and RGB)
- CMYK-based device dependent colour spaces (CMY and CMYK)

The profiles may be used to tag images, for example described in TIFF or PostScript format (see §4.2.3), with device-specific information to facilitate their correct rendering. In addition, the profiles are designed to be plugged together by the controlling software (known as the colour matching module).

Part of the ICC profile includes a *colorimetric context* which is used to record colour appearance related data such as descriptions of the viewing conditions or imaging media. However, how this information is actually handled is beyond the scope of the profile format itself and must be dealt with externally by the colour management software.

4.2.3 Colour Communication

For successful colour communication, colour fidelity is only half the story. A number of levels on which colour communication can take place within a computer system are identified in [Walk93a].

- colour space to colour space
- CMS to device (or *vice versa*)
- CMS to CMS
- application to application
- computer platform to computer platform

Equally important as colour fidelity is the representation that is used. Although every effort is being made by the ISO to define a standard for device independent colour within its Office Document Architecture (described later in §5.3.2), many users have more immediate requirements. Two current *de facto* standards which currently fulfil these needs are introduced next. Walker also reiterates the point made earlier that device independent colour data is ambiguous and to be interpreted properly requires the addition of information defining the viewing conditions and imaging medium.

The *Tag Image File Format* (TIFF) [Aldu92a] describes *raster* image data (depicting bilevel, greyscale, indexed or full colour pictures) which usually originate from computers, scanners or frame grabbing hardware. The standard aims to be both portable and extensible and comprises of a rich variety of fields (describing various image attributes) all of which application software may or may not decide to make use of. Using this format, colour images can be described in terms of RGB, CMYK, YC_bC_r [CCIR90a] or using a device independent specification. TIFF currently supports CIELAB as a means for the device independent encoding of images. Device independency may also be achieved for RGB images by including calibration information relating to the RGB data. With the inclusion of fields defining the white point and RGB primary chromaticities together with a "transfer function," it is possible to relate image RGB to CIE 1931 XYZ values. The transfer function, in this instance, is used to describe in tabular form any pixel coding (such as gamma correction or quantisation) that might have been applied. In addition to supporting a variety of means for specifying colour, a number of different image data compression schemes are supported to reduce the overall storage requirements. These include Lempel-Ziv and Welch [Welc84a] and also the JPEG [Gonz92a] standard.

PostScript [Adob92a] is somewhat different to TIFF in that it is actually a device- and system- independent *page description language* (PDL). Although highly oriented towards drawing text and graphics on a page,† it is capable of being used as a general purpose programming language. As such it is highly flexible, however this has to be balanced against the increased cost of complex interpreters and powerful hardware (called a *raster image processor* or RIP) that is typically needed to interpret the language. PostScript incorporates the RGB, HSB (hue, saturation, brightness) and CMYK (device dependent) colour models for colour specification and provides the mechanism for control over various (device dependent) elements of the printing process, including the production of colour separations, overprinting, undercolour removal, black generation and halftone screens. In its most recent incarnation, *PostScript Level 2*, a number of new features were added including support for device independent colour and data and image compression. Device independent colour specification is achieved through the application of CIE colorimetry. Using a two-stage non-linear transformation [McGi92a] of the original CIE 1931 XYZ space, an arbitrary number of colour models, known as "CIEBasedABC," are defined. Special cases of CIEBasedABC spaces include CIELAB (but not CIELUV), calibrated RGB, YIQ and YUV (respectively used in the NTSC and PAL television systems [Spro83a]) and, trivially, the CIE 1931 space itself. Together with a colour's specification in terms of ABC, the colour component range, white and black points can also be specified.

In [Kass92a], it is argued that the majority of these "standards" merely provide a *framework* for device independent colour. Specifically, they do not stiplulate which colour space should be used to represent colour; the responsibility for this is left to the user or software designer. To help remedy the situation, Kasson and Plouffe procede to discuss the requirements for a general-purpose colour interchange space. The most fundamental of these requirements is that the (device independent) colour space should "see" colours identically to human observers. A number of suitable spaces were examined, considering such attributes as:

† The concept of a "page" is equally applicable here to the display screens of interactive systems [Adob92b] as it is to the printed page.

- exact transformation between international standards
- extent of gamut coverage
- compactness and accuracy
- computational complexity

The paper concluded that of those spaces studied, the best interchange spaces were CIELAB and YC_bC_r (c.f. Buckley's study in §4.2.1).

4.2.4 Summary

Colour fidelity and colour communication across a variety of different media are inextricably linked and together form a desirable yet elusive goal for modern WYSIWYG computer systems. In this section, it was seen that to achieve these critical requirements, a combination of device and viewing condition independency, together with standards for the communication of colour information are required. A survey of current colour management systems revealed that the main emphasis was on colour matching between screen and printer with much less regard being paid to colour communication (possibly due to the lack of standardisation in this area). Also, the systems tended to provide only a very limited choice of models for colour selection or editing. Another limiting factor to the success of such systems is that device profiles still tend to be system-specific and cannot be exchanged with other CMS (although recent standardisation is likely to overcome this). Furthermore, it is frequently the case that systems provide only generic profiles for an entire class of device. If a particular printer, for example, differs from the system's role model, discrepancies can arise. Few current systems (EFI being one notable exception) permit the user to update the calibration data in order to take such differences into account. Finally, there would appear to be at present a multitude of proposed CMS architectures, but much less in the way of high performance algorithms for maintaining fidelity.

4.3 COLOUR SPACES ON VDUS

Introduction

Traditionally, colour specification systems have been presented (and often defined) in terms of physical samples such as painted chips or dyed fabric squares. However, these forms are prone to colour change or damage through their day to day use. Furthermore, they exist in limited numbers which means that they must be reproduced should additional copies or different shades be required. Since the introduction of colour computer-controlled displays, users have struggled with the task of selecting colour using only device primaries (i.e. by directly controlling the intensities of red, green and blue light that is emitted by the CRT phosphors). Various attempts have been made to provide a more convenient user interface to colour selection through the use of systems employing perceptual attributes of colour.

In [Trav92a], the features considered important for a "good" colour space are given as follows:

- *Perceptual uniformity.* Equal steps within a colour space should be perceived as having equal visual spacing.
- *Navigational ease.* Moving around the colour space should be an intuitive process.
- *Relationship to the human visual system's physiology.* This is mainly useful for research purposes or for assessing colour vision.
- *Accuracy of colour specification.* This is important where colour needs to be reproduced accurately on some other device (such as hardcopy) or where two or more displays needs to be matched.
- *Ease of implementation.* The colour space should be implementable (and ideally, computationally easy to use) on an electronic display.

The relative priority of each item is regarded as being application-specific. An additional requirement not given here is to be able to accurately correlate screen colours with physical samples or standards (i.e. to locate screen colours, rather than simply being able to print them out). In this section, a survey is made of some of the previous and existing work done in the area of representing various colour spaces on computer displays. The study concentrates on perceptual colour spaces as the non-perceptual systems (such as RGB and CMY) can usually be trivially derived from a particular display device's primaries. Consideration of human factors is also important for interactive systems; it was demonstrated in [Berk82a, Berk82b] that users perform colour selection more accurately using colour spaces *both* employing perceptual attributes and defined using familiar natural language terms.

Perceptual Colour Spaces

Use of perceptual colour models has a number of advantages [Robe83a]:

- The provision of a natural, intuitive method for describing colour attributes.
- Separate control of lightness and chromatic contrast.
- Uniformity along each attribute axis: one numerical unit corresponds to one perceptual unit of change.
- Device independency. The user's mental picture of colour is (logically) isolated from the actual representation in device coordinates.

Despite the obvious advantages, it is by no means uncommon to find that only non-perceptual colour spaces are available for colour selection in some computer systems.

The use of colour spaces in computer graphics is introduced in [Jobl78a] and details are given of a number of spaces suitable for user interaction. It is argued that the additive RGB space commonly found on computer systems is often ill-suited for colour composition applications. Users with some artistic experience are often more proficient at using CMY subtractive primaries since these correspond more closely to the process of mixing paints. However, it was also pointed out that most people notice the hue of a colour first, followed by such properties as lightness, brightness and saturation. These characteristics are therefore more natural for the untrained user to use during interactive colour specification tasks. The paper then goes on to give examples as to how such attributes may be used to calculate the corresponding RGB values. Some schemes for representing a three dimensional colour space on a two dimensional display are also given and finally other computational uses are given for colour spaces (e.g. image synthesis).

It was demonstrated, in [Meye87a], how uniform colour spaces such as Munsell and OSA-UCS could be reproduced on computer displays for use as a colour selection tool. (Some other applications for uniform colour spaces were given, such as colour coding or determining the colour resolution necessary for communicating images.) The authors also give details of how a display can be accurately measured and adjusted in order to calibrate it in terms of CIE XYZ. The display of the colour spaces was matched to the conditions that existed during the measurement of the data upon which the spaces were based; i.e. reproducing the same size and spacing of the original samples together with identical chromaticity and luminance of the background and light source. One of the main problems encountered in this work was that of colour gamut limitation.†

A "computerised colour atlas" (CCA) was developed by [Dere85a] based on the NCS, CIELAB and CIELUV systems. These three systems were chosen in an effort to provide a means of colour selection appropriate to a number of different tasks. To calibrate the display, the monitor's white point was adjusted to correspond to that of the CIE standard illuminant C and *all* of the sixteen levels‡ producible using each gun were measured using a photometer. It was then possible to compute the tristimulus values for given RGB values (and *vice versa*). XYZ values could then be transformed onto the CIELAB and CIELUV spaces [CIE78a]. The NCS approximate notation was found via CIELAB according to [Dere83a, Dere86a]. The CCA supported interactive colour selection from either of these three colour spaces. A subset of the NCS database was later analysed [Dere90a] by making a visual comparison between screen and physical atlas colours. It was noted that there exist some differences in CIE values and these were attributed to the different measurement instruments used to measure the NCS atlas samples and computer VDU. The study recommended that the background luminance be specified as part of the definition of a colour notation system as screen colours are highly susceptible to simultaneous colour contrast and can even change their appearance from luminous to non-luminous mode.

This work was further continued [Hedi90a] to include facilities for palette creation and modification. Using this later system, colours could be selected from CIELAB or NCS spaces or by using a natural language colour naming scheme. In each case, a menu listing the names of available colours was presented to

† In this instance, the pigment gamut of the Munsell atlas was thought to be the limiting factor, rather that the CRT.

‡ The display was capable of displaying only 256 out of 4096 colours at any given time.

the user. Colours could also be plotted on CIELUV or NCS diagrams, although direct selection was not possible from these graphical displays. The system was able to search for certain other "related" colours; e.g. choosing suitable shades which are legible when used for textual information to be placed over a given colour. Also, it was possible to create colour scales by interpolating between two given hues. The colour palette was presented in a border surrounding the main ("working") image and could be used to change selected portions of this image.

Other Systems

A number of other computer-based systems exist for colour selection or manipulation which do not directly employ the colour spaces previously mentioned. The following subsection covers such systems and also those which apply existing colour models to computer displays in novel ways. One use not detailed here is that of selecting visually distinct, meaningful or otherwise appropriate colours to be used for coding data, e.g. cartographic images [Gill88a]. However, as will be seen, similar techniques can be applied to colour selection for graphical user interface design.

The use of perceptual colour models in the creation of user interfaces for modern colour graphic workstations is also advocated in [Baue91a] which states that colour can improve the usability and efficiency/productivity. It is argued that the colour tools supplied in such a system should be task-related. The typical colour models used are often computer hardware-oriented or founded on the human visual system; these are generally not intuitive for the non-expert colour user. Furthermore, it is claimed that many of the existing tools are "modal and indirect," i.e. colour manipulation is performed in isolation from the other tools. This often results in the inability to visualise how the colour would actually appear when it is ultimately used in some other system tool. One real example of of this is given as the *Apple Macintosh System Color Picker* [Comp86a] which when invoked, presents its display window such that it almost completely obscures the main application's display area, leaving the poor user to guess as to how the colour will look in place.

Therefore, the authors propose the need to be able to view colours in context and recommend the use of user- rather than machine-oriented tools. Perceptually uniform colour models are recommended as being the most intuitive to use (e.g. making it easy to perform colour adjustments such as changing a colour's lightness), however it is noted that the choice of colour model alone is insufficient: this is only one aspect of the user interface. Functionality is held to be more important and it is recommended that users should be able to manipulate colours in ways which address the tasks that they perform. This would, therefore, imply that any colour tools are likely to present a *domain-dependent* solution to users' needs.

Perception and likely usage of colour are shaped by any previous training that the user may have experienced. One scheme often used for graphic design and art training is that given in [Albe63a]. This method emphasizes the perceived effects of colour interaction (such as simultaneous colour contrast) and, it is argued, can also be used as the basis for constructing better user interfaces for colour computer tools. (One example of such tools is the "3D Perceptual Picker" which is used for design-oriented colour selection. This is discussed later.) Bauersfeld and Slater [Baue91a] conclude that colour tools must anticipate the users' activities and their perception of colour. Tools should also be aware of the relationships that exist between colours. Also, perceptually uniform colour models should be employed and these should be able to preserve the working context.

When learning to work with colour, designers and artists tend to learn general principles and develop their own intuition as a result of their experiences. According to [Albe63a], it is not possible to explicitly produce rules defining the perceived behaviour of colours when they interact with one other. Consequently, algorithmic prediction of the appearance of complex scenes has been difficult to accomplish. A means of assisting with the colour selection process using artificial neural networks was developed [Salo89a]. This was primarily aimed at aiding users with the choice of "suitable" user interface colour schemes (i.e. "related" colours which present sufficient contrast so as to be visually distinct without appearing garish). The chief advantage of using neural networks is that they can be trained rather than requiring explicit rules. Training data was obtained by having experienced graphic designers select these "suitable" groups of colours for a limited number of interface objects. The data itself consisted of several display RGB values for each group of colours.

Once trained, the resulting neural network was able to suggest other "suitable" colours based on a smaller number of preferred colours that are suggested by the user. The system was evaluated by having a panel of users generate colours both in this way and also by random selection. The resultant colours were then (subjectively) rated by the user according to their like or dislike for the chosen colours. The results showed a significant preference for those colours generated by the neural network over those generated at random, however it was also concluded that no *single* tool for colour selection could hope to satisfy every individual's colour tastes. It was concluded that the main usefulness of the system was in suggesting colours which could subsequently be refined by the user.

A similar approach to this was carried out by [Meie88a, Hart87a] using expert system technology, rather than neural networks. However, this approach *did* require that explicit rules be given concerning the effective use of colour and these first had to be compiled from various sources.

One fundamental difficulty involved in the presentation of colour spaces is that these are essentially three dimensional in nature and it is invariably required to project them in some way onto a flat two dimensional computer screen (at least until colour stereoscopic or holographic displays become widespread). Typically, this is done by depicting one or more 2D cross sectional views through the colour space. However, this only presents part of the available colours at any one time and can often be difficult for inexperienced users to comprehend. Physical 3D colour models, such as the Munsell tree [Macba], exist and are widely used by designers to represent colour spaces. Work has been done to create a computer-based colour selection tool [Baue91a] employing a pseudo-three dimensional presentation of the Munsell colour space. A study was first made into how the Munsell tree is used by designers. This revealed that the tree was mainly being used for colour space visualisation, whilst the actual task of colour selection took place using the 2D Munsell atlas. The relatively static nature of the tree compared to the atlas was found to be the cause. In implementing a computerised 3D Munsell atlas, it was hoped to combine the benefits of both forms of the physical atlas which were already familiar to many designers.

On screen, a view of the Munsell colour space was presented in a similar form to the Munsell tree (in 3D). However, a single 2D hue page (corresponding to a page from the Munsell book) was always visible (and facing forward) for colour selection. Different hue pages could be chosen and shown. Since the size and shape of a colour patch affects its perceived appearance, all the colours displayed on the current page were of equal dimensions. (However there were no gaps between them, unlike the Munsell atlas, which would therefore lead to Mach banding† at the periphery of each colour patch. It was argued that such gaps might disrupt the perceptual nature of the color space.) The rest of the display presented a perspective view and so it was not possible to maintain the same size there.

For the purposes of evaluation, users attempted colour selection tasks and then completed a questionnaire rating the performance of the 3D picker relative to the exiting 2D (HLS) colour selection tool. The results showed that most subjects preferred the more appealing 3D representation and all thought it more suitable for at least one class of task.

Summary

Existing work done to apply colour spaces to VDUs has been reviewed in this section, beginning with what characteristics a colour space should ideally possess. Perceptually based spaces were recommended for colour selection tasks and a number of practical systems employing them were described. Many of these are modelled on existing physical specifiers, such as the Munsell Book of Colour. An important factor to be considered when providing colour selection tools is that these should not isolate colour from where it is to be used (i.e. it is important to be able to view it in context). Furthermore, the interaction between colours (particularly in user interface design) is also a complex issue which the user needs to be aware of when making a selection. It was argued that colour tools are likely to be task- or domain-dependent at least in part. Finally, the problem of representing a 3D colour space on a 2D screen was mentioned. Presenting a 3D perspective view, although perhaps visually more appealing, can affect the perceived appearance of colours if they are depicted as differently sized regions. Hence, presentation is of fundamental importance.

4.4 INTERRELATION OF COLOUR NOTATION SYSTEMS

Introduction

A colour notation system is a systematic means by which colours may be described or arranged. There are

† The apparent gradation of colour over a uniform colour patch caused by colour contrast at the edges common to two patches.

a number of these systems available at present, existing as both physical samples (colour order systems) and mathematical models. The typical uses for such systems include colour selection and colour specification. Certain systems are quite often used for specific tasks (e.g. photography and CIELUV), in specific environments (e.g. CMYK is used in the graphic arts) or on a national basis (e.g. Scandinavian countries use NCS). Furthermore, users often become very familiar with one particular system and can find it difficult to learn new systems. The real problem, however, lies in the fact that users of "incompatible" systems frequently have considerable difficulty in communicating colour information with one another.

In this section, a survey is given of some of the more notable existing solutions to the problem of converting colours between different notation systems. Although much work has been done in this area to relate individual *pairs* of colour systems (often for comparative study), there are still some missing pieces. As many systems are themselves specified in terms CIE XYZ, this CIE standard is often used as the starting point for deriving mathematical mappings between colour systems. (For complete interrelation, bidirectional mappings for each system are required.) Few attempts have been made to provide a more comprehensive multi-system interrelation.

NCS and CIELAB

Work was done by [Dere86a] to transform NCS data to their equivalent points in the CIELAB colour space. The main motivation behind this study was to establish a relationship between the two colour spaces. This transformation is relatively straightforward and is via CIE XYZ. Data from [SIS82a] was used as the aim points (using illuminant C throughout). Using the CIE colorimetric values contained in this database, the CIELAB L^*, C^*_{ab} and h_{ab} attributes where computed according to their definitions in [CIE85a]. The study concluded that there is *no* simple relationship between the two systems.

Munsell and CIE

An algorithm was developed by [Rhei60a] for the conversion of colorimetric data to Munsell attributes (Munsell Hue, Value and Chroma). The data used was from the renotation system described in [Newh43a] and extended with further data from [Schl58a], both of which are specified for CIE illuminant C. A graphical method was used to derived relations between the two systems of the form:

$$V = f_1(Y),\ H = f_2(x, y, Y),\ C = f_3(x, y, Y)$$

The functions f_2 and f_3 were defined by interpolation of the aim point database. (Since the data defining these were obtained experimentally and are subject to error, it was not feasible to derive functions analytically.) Function f_1 uses a Newton-Raphson method to find the inverse of the polynomial

$$Y = 1.2219\times10^{-2}V - 2.3111\times10^{-3}V^2 + 2.3951\times10^{-3}V^3 - 2.1009\times10^{-4}V^4 + 8.404\times10^{-6}V^5$$

defined in [Newh43a]. A refined version of this method has since been developed by [Simo87a].

OSA-UCS and Munsell

An initial problem was that these two systems were defined for different CIE conditions: Munsell for 2°/C and OSA-UCS for 10°/D65. However once physical samples for both became available, it was possible to compare these systems directly. A set of Munsell notations for the OSA-UCS set were published by [Nick78a] and later analysed [Nick81a]. However, no analytical transformations were derived between the two systems.

DIN with NCS, Munsell and OSA-UCS

Several articles (written in German) give details of interrelation of the DIN system with NCS [Dori81a, Dori83a], Munsell [Budd55a, Kund55a] and OSA-UCS [Witt81a, Witt83a] systems. Elsewhere, in [Smit92a], it was attempted to relate both the NCS and DIN systems to OSA-UCS (again, via CIE XYZ). Points from the OSA-UCS atlas were mapped onto NCS colour space using the measured atlas data given in [MacA78b]. (This was necessary because the two systems were originally defined for different observer/illuminant conditions, however there was still an error present in the mapping due to differences in the geometry used for sample measurement.) This mapping was used as part of a large (multi-system) computer program described later.

Munsell and NCS

There are two principal differences between these systems. Firstly, there is no concept of "lightness" (analogous to Munsell Value) directly available in NCS, although it is possible to derive this. Secondly, the Munsell system was designed such that its attributes have equal visual spacing; NCS, meanwhile, does not embody visual uniformity but instead has the notion of a shade's resemblance to certain "elementary" colours. An analytical comparison of the two systems was made by [Judd75a] and this was used as the basis of further work by [Bill87a] to interrelate the NCS and Munsell systems. The latter work used the colorimetric definitions given in [SIS82a] and [Newh43a] for the two systems, however differences in the measurement instruments and the conditions used for measurement meant that this data was not strictly comparable. Various relations were derived between each of the corresponding attributes (chroma-chromaticness and value-blackness) using these colorimetric databases. No analytical relationship could be obtained between the two hue scales, however, as it was concluded that Munsell Hue was additionally dependent upon both NCS blackness and chromaticness (with further evidence suggesting significant irregularities in Munsell Hue).

Multi-System Interrelation

More comprehensive work for converting between *multiple* colour notation systems has been done by [Smit90a]. This work covered the NCS, Munsell, OSA-UCS, DIN and Coloroid colour order systems together with the CIE, CIELAB and CIELUV colour specification systems. Various aim point databases were acquired and verified and then computer software was written for their interconversion using the CIE XYZ system as a common reference point. Conversion between two systems was achieved by first mapping the given colour in the source colour system onto CIE space. This could then be converted to the target system's attributes. The study identified two key problems:

- Interconversion between systems defined for different *viewing* conditions was not thought to be possible. Dissimilar illuminants, in particular, would result in significant differences.
- Similarly, differences in *measurement* conditions (such as geometry or inclusion/exclusion of the specular component) can also cause large discrepancies.

The suggested solution to these problems was to acquire databases covering *all* available combinations of illuminant, observer and measurement conditions. However, the implementation developed was slightly less ambitious: only data for a limited set of viewing/measurement conditions was used (although the system was extensible so new data could be added as required). Where conversion was requested between systems defined using dissimilar conditions, an error message was displayed. Furthermore, it was asserted that it is not possible to correct for differences in the viewing conditions between systems.

The Munsell-CIE transformation followed the algorithm developed by [Rhei60a] and its inverse used 3D interpolation of an aim point database obtained by the merger of the results of [Newh43a] and [Judd56a] (both defined for illuminant C, 2° observer only). The NCS aim point database consisted of data from [SIS82a] for illuminant C, 2° observer and D65, 2° (obtained from the Scandinavian Institute). Conversion was achieved by 3D interpolation of the subset of this data contained in the NCS atlas [SIS83a]. This subset (containing 2211 points) was chosen over the full database for "ease of data manipulation" and was argued as being a representative and methodical sampling of the NCS colour space. However, it was also necessary to use an extrapolation technique to estimate the missing aim point data (in order to extend the range of the aim points).

The DIN data used was defined for C/2° [DIN81a], D65/2° [DIN80b] and D65/10° [DIN81b], as published in the German industrial standards. Conversion between CIE and DIN (and *vice versa*) followed the methods described in the aforementioned three documents. Additionally, the measured data of actual atlas colours for C/2° and D65/2° conditions were obtained. Again, 3D interpolation was used to convert colours that lie within the DIN colour space to/from CIE XYZ. The CIE/OSA-UCS mappings used the D65/10° data given in [MacA78a] and equations given in [MacA74a]. These equations provide a direct transformation between CIE and OSA-UCS, however a reverse mapping had to be derived (once again, using 3D interpolation of the aim point data).

Both the CIELUV and CIELAB systems represent direct transformations of CIE XYZ space (the transformation being to achieve perceptual uniformity). The definitions given in [CIE85a] were applied to C/2°, D65/2° and D65/10° viewing conditions in order to convert to and from XYZ. Finally, interconversion between CIE XYZ and the Coloroid system was also achieved (for C/2° and D65/10° conditions) through the implementation of the method described in [Nemc80a].

The performance of the software implementing these algorithms was also tested by Smith *et al* using a total of forty-seven "representative" Munsell atlas sample points. These were mapped to each of the other systems' coordinates and back again. (The Munsell system was evaluated by means of forty-seven colours selected from the DIN atlas.) A comparison between these yielded an error of 0.5 or less CIELAB colour difference units. However, some of these points failed this conversion for DIN and OSA-UCS due to the converted points lying outside of the colour space defined by either aim point database.

Summary

In this section, a number of existing techniques for the conversion of colour data between notation systems have been summarised. While it can be seen that such interrelations are possible for many very different systems, there are still a number of obstacles to be overcome. These are:

- the inability to (accurately) convert between systems which are each *defined* for different conditions (e.g. dissimilar light source or viewing geometry). It may also be required to actually *view* the colours under different conditions (e.g. light source or media).
- incomplete mappings: interrelation between arbitrary systems is not always possible since such a mapping may not exist.
- the lack of visualisation of multiple colour notation systems. As was seen in §4.3, colour systems *can* be faithfully reproduced on a suitably calibrated colour monitor; however it is not common to display more than one system. Multi-system presentation is useful for comparing several colour systems visually (to judge their performance or to learn about their characteristics) or simply to extend the choice of colour selection sources. In this context, it can be used to evaluate or confirm the accuracy of the colour interconversion process.
- the failure to convert colours which lie outside the colour space of either the source or target (often defined by a set of aim points).

It should be noted that it is unlikely that the latter problem can be circumvented without having to redefine those colour systems which are effected.

4.5 COLOUR IN DESIGN SYSTEMS

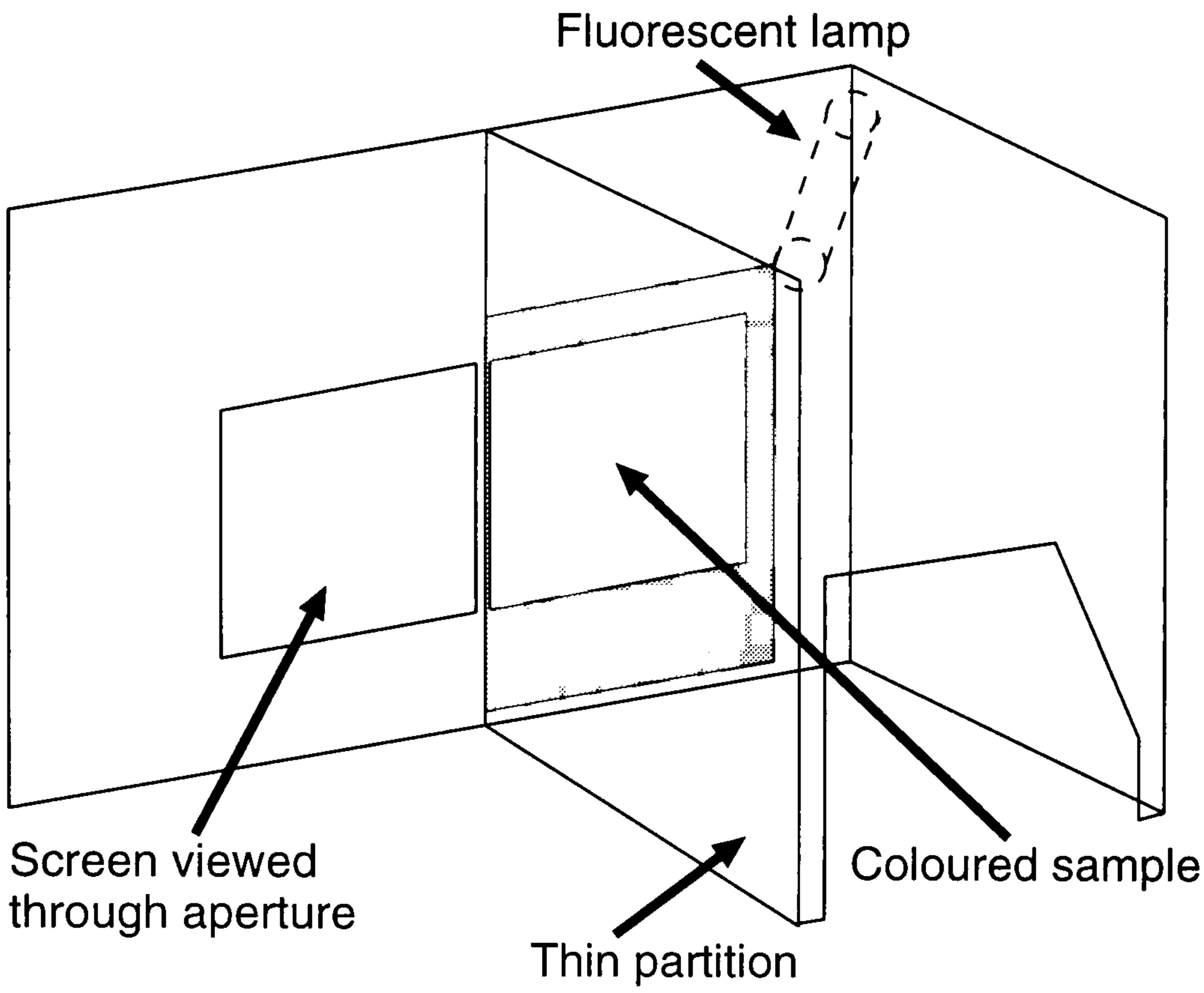
Much of the work of textile designers relies upon the effectiveness of modern computer-based design systems, however colour fidelity has, in the past, largely been overlooked. Yet it is this element that can determine the success of a design and often leads to considerable "wasted" time spent attempting to get shades to appear as intended. In recognition of this fact, a number of CAD system suppliers are beginning to incorporate colour management facilities into their products and it would seem that the trend is likely to continue. This section reviews some of these systems, although it must be realised that since most are proprietary, little technical detail is publicly available.

One system, whose implementation has been published in at least some detail, is the UMIST Shademaster system [Hawk91a, Anon93a]. The system consists of a personal computer system with colour monitor, and a Minolta CA100 colorimeter (used for screen measurement). Its primary aim is to provide precise, reproducible screen colour as part of a tool for designers to create and specify their colour ideas. The system's main features are summarised as follows:-

- on-line monitor calibration for establishing and maintaining repeatable colour
- simulation in pseudo-3D of the viewing booth interior
- colour specification in terms of either CIELAB or XYZ
- generation of synthetic reflection curves for screen colours
- colour manipulation tools

The system's colour manipulation tools centre around colour tiles which may be grouped into colourways. The screen shows twenty-five tiles which overlap one another. Individual or groups of colours may be moved around between the tiles. Pairs of existing colours (the exact means by which they are chosen was not specified) may be used as input to a "colour range" facility. This generates a number of intermediate colours at uniform gradations between the two specified colours.

Figure 4.3: Shademaster Viewing Conditions



For visual matching between surface and screen shades, Hawkyard *et al* advocate the use of a special viewing booth. This consists of a light box and computer screen placed directly adjacent to one another with a mask in front covering the edges of the screen and light box (see Figure 4.3). This, it can be argued, is a somewhat artificial viewing condition such that, when the same colours are later viewed in isolation (i.e. surface *or* screen mode only), there is no guarantee that those colours will still appear the same.

The basis for much of this work is that VDU colour can be made to match a particular surface colour when viewed under a specific light source (since an object's reflectance curve characteristics are independent of illumination). However, when a colour is created using the computer no definite reflectance curve exists,† even though the CIE XYZ values may be known. This leads to difficulty in reproducing such colours in such a way as to maximise colour constancy — since there is no physical colour with which a comparison can be made and also because tristimulus values cannot be computed for other illuminants. Shademaster tackles this problem through the use of "synthetic reflectance curves" [Hawk93a]. Once

† Actually, the colour's spectrum *can* be measured directly from the screen however this is of little practical value due to the spikey spectral nature of CRT phosphors. Attempting to reproduce such spectra on, say, dyed fabric is likely to prove to be expremely difficult (if not impossible) and inpracticably costly.

generated, these enable computer-based match prediction software to compute the recipes required to produce physical samples. The method, it is claimed, exhibits a "good" level of colour constancy, however there are likely to be a number of problems with this approach (see §6.4.3). More fundamentally, a spectral match can fail due to either instrument metamerism (e.g. where geometry affects the results) or observer metamerism (although this is much less significant). Even if two colours yield the same colorimetric values as a result of carefully selected spectral reflectance properties, traditional colorimetry is unable to say whether they will match if the viewing conditions are non-identical. Other factors, such as texture, can also affect the success of an appearance match between screen and surface samples.

The accuracy of colour reproduction of the UMIST system was investigated using forty colours chosen to lie uniformly within the Munsell colour space. These colours were reproduced on the CRT display, measured using a colorimeter and the difference between the target colours were computed. The results shown in Table 4.1, whilst apparently acceptable, where not conclusive for the following reasons. Firstly, only chromaticity (i.e. x, y values) was studied and the results (Δx and Δy) were non-uniform chromaticity coordinates, as opposed to colour difference units (ΔE), which might have proven more meaningful. Also, the total number of samples is quite small and there was no comparable study made of the short-term and long-term repeatability of these results.

Table 4.1: Shademaster Colour Reproduction Accuracy

	Average deviation		**Maximum deviation**	
	x	y	x	y
10 neutrals	0.0018	0.0023	0.003	0.004
10 dark shades	0.0037	0.0058	0.009	0.015
10 medium shades	0.0020	0.0080	0.004	0.007
10 pale shades	0.0024	0.0013	0.006	0.002

Some other design systems employing high colour fidelity are available although, being commercial products, their inner workings are not publicised. Such systems include the Stork Image-3000 CAD station [Anon92a] which supports the design and production of screen printing screens. Part of this system, known as the colourist's colour manipulation system, supports colour selection, manipulation and storage with colours being shown on screen faithful (it is claimed) to their eventual appearance on printed fabric. This enables various colourways to be previewed without the expense of producing samples. There is also provision for a link to a Coats Colour Physics System for colour measurement, recipe prediction and quality control functions. Another CAD system, produced by Sophis Systems [Moor92a], aims to achieve a close match between monitor and printed colours. Its colour prediction software matches designs printed on paper although the ultimate aim is also to match with fabric printing. The system also supports colour selection from existing shade libraries (which might, for example, include a number of Pantone or NCS samples).

In this section, it has been shown that there is a growing interest in the application of colour management technology to CAD in industry (particularly in the textile industry). However, its use is by no means widespread and the current solutions fall considerably short of a complete solution to users' problems. Before concluding this chapter, the next section takes a brief look at how practical the notion of high fidelity colour on computer displays really is.

4.6 LIMITATIONS

Thus far, much attention has been paid to illustrating the success story of achieving good colour fidelity on computer displays and in applying this to computer-based design systems. However, before concluding this chapter, it is worth looking at what the limitations of the technology are.

Experiments have been carried out by Berns involving the assessment of both painted surface samples and CRT-generated colours [Bern91a]. The aim of this work was to look into the feasibility of using CRT technology for colour difference judgement. The experiments were conducted by a panel of observers who were asked to scale colour differences. Colour difference pairs were viewed and a judgement was made as to whether the perceived difference was larger or smaller than an anchor (reference) pair. The anchor pair used were near-neutral having a colour difference of 1.02 ΔE^*_{ab} units. Seven difference pairs were produced from a single green "colour centre" and were used in these experiments. (These difference pairs varied in degree and nature of difference from the colour centre.) In the case of CRT-generated pairs, observer answers were fed directly into the computer, whereas a score sheet was used for surface samples. Matching was only done using *one* media at a time (i.e. using either the CRT *or* surface colours) and hence the possibility of observer metamerism arising from the different spectral radiances was eliminated.

The results revealed that inter-observer uncertainty was highest for CRT-generated stimuli. A number of possible explanations were suggested for this. The surface colours used were glossy acrylic lacquers. Although specular reflections were eliminated during observer estimations, the observers would still have been aware of the effect (which was not present for CRT colours). Also, image sharpness was greater for surface samples. A further difference in conditions was that the viewing distances were not identical. Despite samples being the same size for both media, the CRT display was located some six inches behind the viewing booth. This resulted in angles of 5° and 10° being subtended for CRT and surface pairs respectively. Another possibility suggested was that although CRT colours are related,† they are essentially luminous and therefore are perceived differently to non-luminous surface colours. There may even be further cognitive differences between the two media.

The results of Bern's experiments successfully demonstrated the feasibility of using CRT displays for visual colour difference evaluation and further demonstrated that colour difference tolerances determined using CRT colours were not significantly different from those obtained using surface stimuli. Despite this, Berns cautions that the same may not hold true for other colour centres due to difference in luminance or spatial and cognitive attributes. Another important factor worth considering is the display hardware. In his experiments, Berns used a 10-bit per RGB channel graphics system. The motivation for this extra resolution was to minimise quantisation error. The vast majority of current displays support only eight bits per channel. It is likely that this would reduce the effectiveness of small colour difference judgements. Work has been done to circumvent this using halftoning techniques [Mull86a], however this introduces texturing which therefore changes colour appearance.

Following on from this, similar experiments were conducted by Rich *et al* to visually quantify CRT accuracy in simulating colour and colour difference samples [Rich92a]. The motivation behind this work was for use with computer colorant formulation where it is advantageous to be able to visualise the colour of new formulations or batch corrections without the expense or delay of having to produce physcical samples. The experiments consisted of two parts:-

† See Chapter 2 for a discussion on related and unrelated colours.

(1) to quantify the accuracy of CRT simulations of surface colours and

(2) to quantify the accuracy of CRT simulations of colour difference.

In both experiments, surface colours (or surface colour difference pairs) were seen in a light booth and compared with their CRT simulation counterparts. The matte surface samples were chosen from the NCS colour atlas; in total forty-eight difference pairs and forty-eight simulation samples were used.

For the absolute colour experiments, observers were invited to estimate the apparent colour difference between the colour of a sample viewed in a booth and one displayed on a CRT. The difference units used were given relative to reference grey scale (anchor) and observers used binocular viewing of sample and simulation. In the colour difference experiments, pairs of colours where placed in the booth and compared with pairs of colours displayed on the CRT (shown side by side and separated by a fine line). Observers were then asked to judge which pair exhibited the largest colour difference. (A forced-choice pair comparison method was used.)

Experimental results showed that surface and simulation pairs did not appear to have the same colour differences. They also revealed that the accuracy of simulating a given colour was colour-dependent (and non-constant). In their discussion, Rich *et al* suggest the possibility that the experimental subjects were not completely adapted to the source neutral poiunt of the CRT (i.e. observers realised that the "white reference" of the screen was not the same as the "white reference" of the booth). Rich also highlighted the issue of colour resolution as being a limiting factor, citing the work of Saunders [Saun87a] which showed that, for an ideal 24-bit colour display, quantisation to a finite 256 steps resulted in errors of 0.5 ΔE^*_{ab} on average and rising to 1.5 ΔE^*_{ab} units for the worst case. Some inter-observer differences were seen in the results which was attributed to observer metamerism which, it is argued, is higher for the CRT simulation. Finally, Rich mentions (as did Berns) the perceptual difference of CRT colours and suggests that this might be overcome by the inclusion of texture and gloss in the simulation. In conclusion, it is stated that CRT displays *can* be used to simulate surface samples and the accuracy of difference pair simulation is dependent upon the accuracy of CRT characterisation (for all but large differences).

To summarise, the work of Berns and Rich has demonstrated the feasibility of simulating surface colours on CRT displays and also of simulating colour difference pairs. While moderate colour difference pairs can be faithfully depicted on CRTs, errors in characterisation or in quantisation make this impracticable for small differences. Further limitations are seen to arise from the perceptual differences between the media however, as was seen in §4.2.1, such differences can be overcome through the application of colour appearance modeling.

4.7 CONCLUSION

In this chapter, we have seen that absolute colour fidelity across different media (so called "WYSIWYG colour") can be addressed by the application of both colorimetry and colour appearance modeling. CAD systems utilising this approach can achieve good results, however the final precision is ultimately limited by both the gamut and (particularly where colour difference is concerned) the discontinuous nature of colour produced by the display hardware. While a number of proprietary systems exist for the management of colour, none currently employs colour appearance and most get around the gamut limitations by applying non-WYSIWYG transformations. A number of different colour specification systems have been reproduced using computer displays, but few are integrated into colour mangement systems. Furthermore, little work has been done to support the use of multiple colour notation systems (possibly due to the difficulty of their interrelation), even though many colour systems are now popularly in use. Consequently, most design systems provide only poor colour selection and communication tools and in general fall considerably short of providing a total solution. Despite this, there is a growing interest in this area and many hardware and software producers are keen to jump on the colour management bandwagon.

Chapter Five
The Proposed Solution

CHAPTER FIVE: THE PROPOSED SOLUTION

5.1 INTRODUCTION

As already mentioned, colour is a potential source of difficulty for designers in industry and for computer users in general. Typical problems facing users of CAD systems include poor colour fidelity, limited (or non-existent) colour management facilities and an inability to accurately communicate colour information. It is not uncommon for users to match to printer output and work with the *wrong* colours on the screen. Not surprisingly, this can lead to errors in colour judgement. Manual colour matching is tedious and time-consuming. Furthermore it is not a productive use of designers' or operators' time and significantly increases the lead time from design to production. Mistakes are frequently costly; having to correct them incurs extra cost and wastes even more time.

In the fashion business, a rapid response to changes in trends is essential in order to maintain market competitiveness. Any scheme for shortening response time would be of immediate benefit to industry. Improving both colour *fidelity* and colour *communication* within existing CAD systems not only accomplishes this but also reduces design cost and creates further opportunities for international trade. In the UK textile industry, it is not uncommon for design work to be carried out in this country while the actual production is done elsewhere, such as the far east. In such cases, maintaining *remote* colour fidelity is also a highly desirable goal.

This chapter proposes one solution to these problems by defining procedures for achieving colour fidelity and precise colour communication. Together with additional tools for colour management, these methods can be applied to most *existing* CAD systems or used as the basis of a *new* system (as detailed later in Chapter 6).

5.2 AIMS

Overcoming most of the colour fidelity problems inherent to conventional computer-based systems is possible through the application of colour science. However, predicting what the exact requirements would be for an arbitrary computer user is somewhat difficult and so the application domain was deliberately restricted to cover just *textile design*. One reason for this choice was that the design processes involved in this area dictate a high profile for colour itself within a design and also require a high degree of colour precision. It was clear from the interviews held with these designers (see Chapter 3) that their current means for achieving this are far from satisfactory. In aiding this design work, the overall aims have been to support the accurate creation and communication of colours in the form of palettes whilst maintaining WYSIWYG colour appearance at all stages. Although specific attention was paid to the textile design industry (where fashion palettes play a critical role), any design environment working with a limited set of colours and requiring accurate colour reproduction should benefit. The specific problem areas to be overcome are the fidelity, specification and communication of colour information.

5.2.1 Colour Fidelity

Employing WYSIWYG colour performance throughout a CAD system has the advantage of eliminating time-consuming visual matching and allows users to work with the correct colour on the screen at all times. It enables colour-critical decisions to be made directly from the display, hopefully with a high level of confidence about a design's final appearance. However, attaining a sufficient level of colour fidelity for this to be practical is not straightforward and requires some effort on the part of both the manufacturer of the CAD system and its end-user. If done properly, though, it can still offer a significant time and cost savings to companies over more conventional means.

The first stage to achieving colour fidelity is to characterise the display in terms of CIE XYZ values. This is typically done by measuring known colours and deriving a model to relate the device primary intensities to XYZ (and *vice versa*). This process, known as *device characterisation*, must be repeated for each of the input (e.g. scanner) and output (e.g. screen or colour printer) devices that are to be used. Note that even "similar" devices (such as two monitors made by the same manufacturer) must be individually calibrated as their colour performance will not be identical.

There are a number of problems with *just* using this approach. Firstly, each device's characterisation will not hold over time. In the case of monitors, the phosphors used in the CRT gradually decay and the brightness/contrast settings may drift or be deliberately changed. For colour printers, the inks used can vary significantly between batches causing differences in colour. This problem can be overcome by periodic recalibration (the frequency of which is device dependent). Once calibrated, the various imaging devices can output colours (e.g. on the screen and on paper hardcopy) which, when measured with a suitable colour measurement device, yield quite similar CIE XYZ colour coordinates. This type of correspondence is known as a *colorimetric match* (§2.3.1). Unfortunately, such use is beyond the scope of CIE system: a colorimetric match is only acceptable when the viewing conditions are *identical*† (§2.3.5), however this is rarely the case. In particular, the *perceived* difference in colour appearance when presented on dissimilar media (such as on a colour monitor and on paper) is highly significant — even though they may seem colorimetrically similar. Other dissimilarities between viewing conditions (such as illumination, background and luminance level) also affect colour appearance and must be carefully controlled. Thus, it can be seen that a colorimetric match is not enough: a model of human colour vision (or *colour appearance model*, see §2.5) is also required to compensate for differences in viewing environments.

One further obstacle to WYSIWYG colour is caused by limitations in the colour gamut of each output device. Different devices are capable of reproducing different ranges of colour and, since their gamut is a subspace of the CIE XYZ colour space, there will *always* be colours which cannot be displayed.

5.2.2 Colour Selection and Specification

Finding exactly the right colour is frequently difficult as most CAD systems provide only rudimentary tools for colour selection. Also, many of the colour models that are used are often device dependent (e.g. RGB, CMY and HLS) and do not exist as physical standards, thus making colour communication somewhat difficult. Other systems employed, such as Pantone, have attributes which have no perceptual basis (perceptual attributes were introduced earlier in §2.6) which makes locating colours an arduous task. Numerous "standard" systems are available for colour selection and each is useful for certain tasks or has its own strengths and weakness (e.g. CIELAB is widely used by surface colour industries whilst CIELUV is often applied to colour television or photography). Different countries also have their own national standards, e.g. NCS (Scandinavian countries) and Munsell (USA and Japan). Furthermore, many users are very familiar with

† That is, using the same background, illumination, viewing geometry and media.

one or two particular systems and are very reluctant to "learn" a new one. However, the main difficulty arises in transferring colours from one colour order system to another when there exists no simple perceptual correlation between the attributes of each system.

Since computer colour is typically non-communicable, designers often have to resort to physical standards, such as fabric swatches, paper, yarn or thread samples. These are often difficult to reproduce and can be of arbitrary appearance. The more sophisticated designer will make use of a colour order system such as the Munsell Book of Colour. Colours can be located from within the pages of this book and their "name" used as a reference when communicating colour. Most (but not all) colour systems have a reasonable degree of reproducibility (i.e. the same colour reference in another set of physical samples will closely resemble the first). Such colour atlases are quite common but suffer from the following drawbacks:-

- *cost* — each set can be expensive to reproduce, particularly if high colour fidelity or "difficult to reproduce" colours are required.
- *fading* — their colour changes with time, particularly if exposed to strong light.
- *contamination* — samples are prone to becoming scratched or dirty through everyday use.
- *few samples* — for practical and cost reasons, a relatively limited number of colour patches are available. This can be problematic when the desired colour lies *between* two or more of the samples provided.

5.2.3 Communicating Colour

Where colours are defined externally, fashion palettes often need to be sent by their creators to the textile designers prior to beginning any design activity. Colour palettes are also exchanged between the designers themselves. After a design has been completed, it usually needs to be presented to the customer (or buyer) for subsequent approval. Finally, once accepted, colours need to be accurately reproduced in the product and this is accomplished by negotiation† with the dye house. This may need to be repeated several times until the final proof appears satisfactory to the designers. Each stage of colour communication typically

† It must be determined in advance exactly what level of batch variation (as quantified in terms of colour difference units) from the target shades is to be tolerated in production.

takes time, is expensive (physical samples have to be specially produced or acquired) and introduces error into the final target shades. Where the viewing parameters for colours are not well defined or colour samples exist in different forms (e.g. thread and paper), some ambiguity in their perceived appearance is also likely to occur.

To solve these problems, colour information needs to be represented in a precise, well defined format. By maintaining a purely numeric representation within the CAD system, an *electronic palette* can be rapidly and accurately transmitted anywhere in the world via modem, electronic mail or computer network. This method is also cheap since no physical samples have to be made up. If CIE XYZ is to be used for colour specification, then the viewing conditions for the colours need to be fixed so that both parties are assured of seeing the same thing. This is actually much easier to enforce using a computer-based system since the format of the display can be carefully controlled by software. Using spectral reflectance data for colour specification avoids problems with illuminant metamerism. It is not generally possible to display or print a colour defined in this way (since an exact spectral match needs to be obtained).

5.3 THE PROPOSED SOLUTION

In this section, one possible solution to the problems of colour fidelity, specification and communication for computer-aided design is proposed. Various recommendations are made as to the steps necessary to overcome these deficiencies. Later, in Chapter 6, an actual implementation of these ideas is discussed. The corner-stone to this solution is maintaining WYSIWYG colour appearance throughout *all* stages of design (including communication) together with the provision of supporting tools for colour management tasks.

5.3.1 Achieving WYSIWYG Colour

As advocated in [MacD90a] and [Bern92a], high colour fidelity can be achieved through device independency and viewing condition independency. There are four steps required to accomplish this; these are as follows:-

1. Device calibration.

2. Device modelling.

3. Apply a colour appearance model for dissimilar viewing conditions.

4. Consider device gamut limitations.

5.3.1.1 Device Characterisation

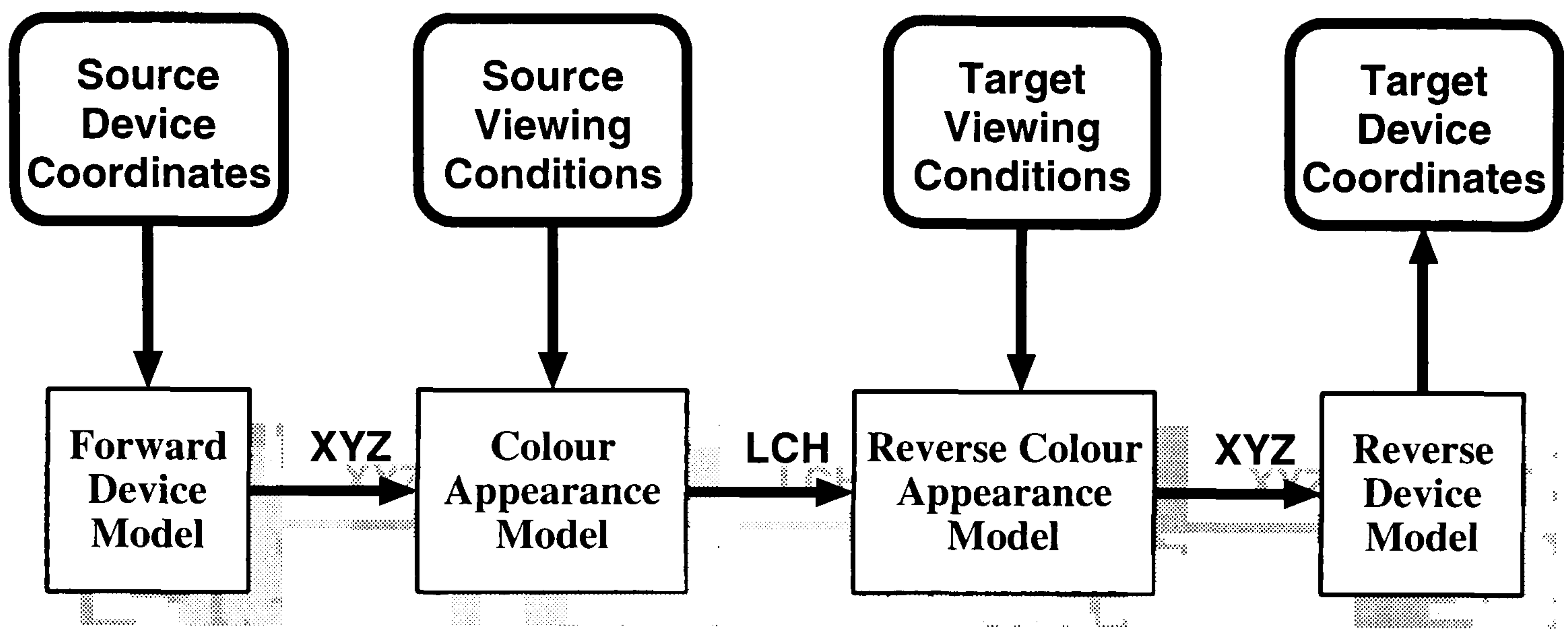
Device characterisation (to achieve device independency) can be broken down into two logically separate steps: calibration and modelling. Device calibration is necessary to ensure a "standard" setup for future colour repeatability. It typically entails adjusting the device's own internal parameters in some way until a correlation with an *external* standard is obtained. For example, a colour monitor may be simply calibrated by adjusting its luminance range via the brightness and contrast controls. (It may also be necessary to adjust the monitor's white point to achieve the correct colour balance and gamut coverage.) Calibration should be performed prior to any characterisation procedures and also at sufficiently regular intervals so as to avoid colour drift (i.e. changes in both luminance *and* chromaticity over time).

The task of device modelling is to derive mappings between XYZ (or some other device independent representation) and device coordinates via a *calibration model.* This requires an initial measurement of generated colours (or input in the case of a scanner) using a colour measurement instrument. For reliable calibration and characterisation, it is recommended that only one instrument be used for all colour measurement (so as to avoid instrumental metamerism between different colour measurement equipment).

5.3.1.2 Use of Colour Appearance Model

As seen earlier, merely attaining a colorimetric match is insufficient to solve all the problems associated with colour fidelity — particularly where multiple media output is concerned. Any dissimilarity between viewing conditions implies a change in the perceived appearance of a colour to the human observer. There are various colour appearance models (discussed in §2.5) capable of predicting such effects. A comparison of these were made in [Luo91b, Luo91c] and it was concluded that the most reliable and general purpose (i.e. that covering the most viewing conditions) model was the Hunt [Hunt91b] model, which has since been revised a number of times [Luo93a, Luo93b, Hunt93a] to improve its predictive accuracy and include other media. This model essentially enables CIE XYZ data, together with specified viewing conditions/media, to be expressed in terms of the model's perceptual attributes (*lightness*, *colourfulness* and *hue*). By deriving a *reverse* colour appearance model [Hunt91a] between the appearance model's LCH attributes and XYZ, this can be combined with the forward model in a *four-stage transform* (or FST) [Yous91a, MacD91a] to predict apparent colour *change* between different viewing conditions or media. This process is illustrated in Figure 5.1. The intermediate LCH perceptual attributes are independent of viewing conditions [Bern92a] and media (cf. CIE XYZ being a device independent representation).

Figure 5.1: The Four-Stage Transform



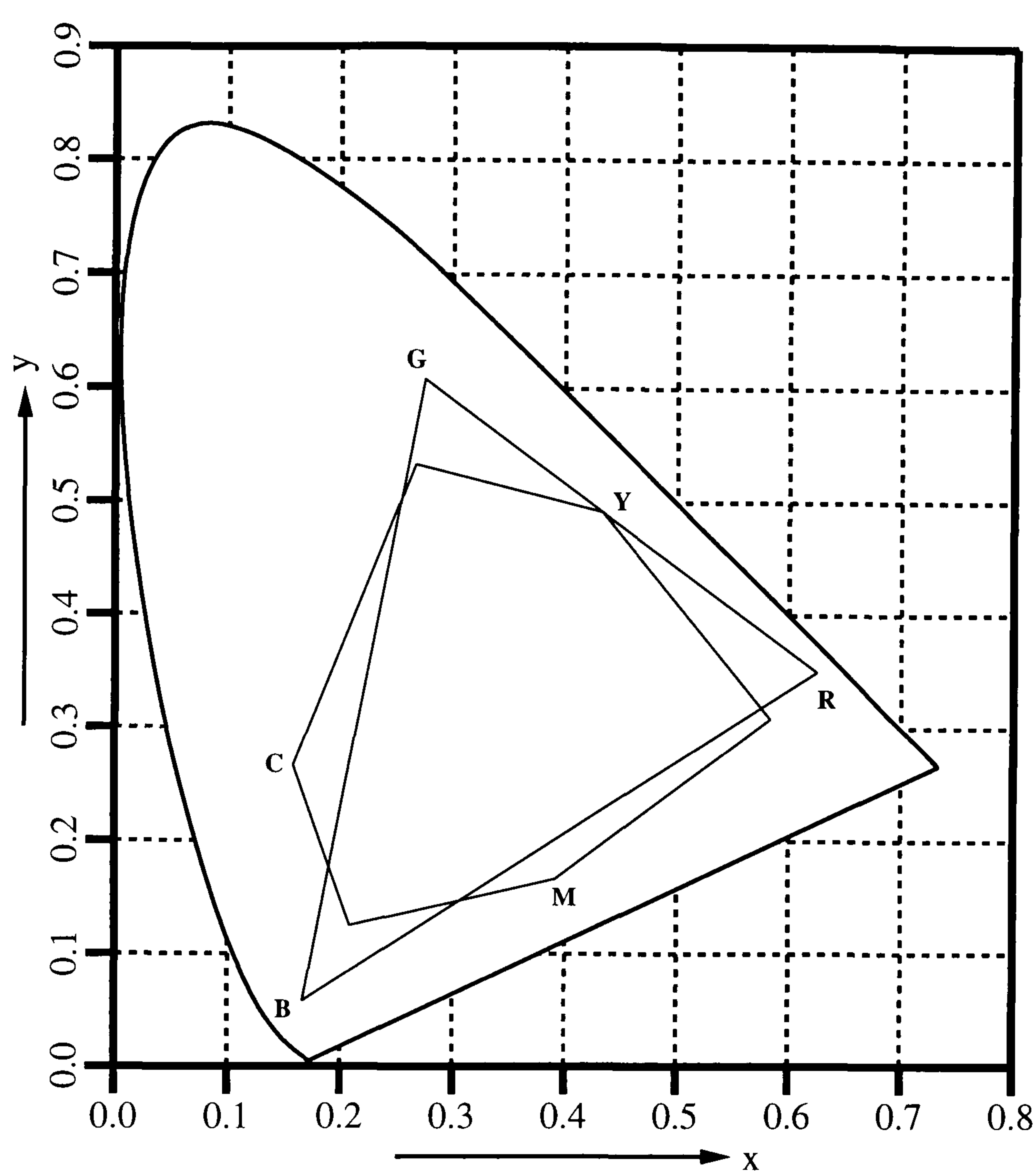
5.3.1.3 Colour Gamut Limitations

Colour monitors and printers are capable of producing a finite range of colours. This is depicted pictorially in Figure 5.2 which shows the colour gamuts of a typical colour monitor and printer within the CIE colour space. Note that the shapes of the monitor (RGB) and printer (CMY) gamuts are very different. The overlapping region defines those colours which can be reproduced using *both* devices. Colours which lie outside of one particular device's gamut cannot be faithfully reproduced using that device (even though they may be displayable on another device). One common technique used to overcome this limitation is through *gamut mapping* (or *gamut compression*), as described in [Ston88a]. This performs a mathematical transformation of the source XYZ values until a "satisfactory" reproduction is obtained. Unfortunately, the problem of determining just what is satisfactory cannot be solved algorithmically and instead has to rely on the aesthetic judgements† of a human. According to [Hunt87a],

† It is often a requirement that the final image be an "improvement" of the original, rather than visually appearing similar to it — particularly where an original image has defects such as being over exposed. Indeed, the job of producing

"The ultimate test of any colour reproduction is the opinion of the person who views it. But opinions differ, and, in cases where dissatisfaction is felt, the viewer often finds great difficulty in saying exactly why he does not like the sensations that he experiences when looking at the picture."

Figure 5.2: Typical Colour Gamut of Monitor (RGB) and Printer (CMY)



The process can be aided through computer visualisation of gamut and simulation of the final image colours, however it still remains a somewhat arbitrary procedure. (The image scaling factors used would necessarily be different for each input-output device combination and would also be image dependent. Also, these factors are usually derived through empirical means.)

Applying gamut mapping techniques precludes WYSIWYG colour performance. Although this is often useful for extending the apparent range of colours that a device may reproduce, it is at the expense of

---

"pleasing" (i.e. *preferred* — see §2.7.3) colour reproductions is highly paid within the graphic arts industry.

an exact colour appearance match. It is, therefore, proposed *not* to use such methods and instead provide some kind of visual feedback (via the computer system's user interface) to indicate where and when gamut constraint becomes a problem. Where a colour lying outside the gamut needs to be displayed, a "close" in-gamut colour (which is easily recognizable to the user as being *wrong*) should be shown. One way of achieving this is through *projective clipping* [Ston88a] which projects back unreproducible colours onto the surface of the locus defining the printable/displayable gamut.

5.3.2 Representation of Colour

For successful electronic communication of colour information, both the data representation and also the viewing conditions (both on-screen and for physical samples) require standardisation. At present, a joint CIE/ISO/ANSI working group [Ales91a], Text and Office Systems Colour Architecture (TOSCA), is looking into the issue of colour representation for document processing by specifying a standard framework of objects. The standard is to be known as the TOSCA Colour Data Interchange Transform (CDIT) Object Framework and will enable the interchange of colour information within an open systems environment. Other standards [Robi91a] are currently being put together in the United States and include the Digital Data Exchange Standard (DDES) for colour (run by IT8†) and also the ISO/TC 130‡ Working Group 2. The IT8 group is working to provide reference colour standards [Maie90a] (e.g. the Q-60A reference [Comp88a] for transmissive media) for both digital and analogue reproduction to be used as a guide for subsequent colour correction adjustments. Further effort is also being given to defining methods for exchanging colour information in a distributed electronic design and production environment. The ISO/TC 130 group's activities are in standardising terminology, test procedures and specifications for global colour data exchange within the graphic arts industry.

Unfortunately, none of these standards is yet complete, let alone widely accepted by industry. Furthermore, the colour communication requirements of textile designers are somewhat different to those of the graphic arts industry (being centred around colour palettes, rather than pixel images). It was therefore deemed necessary to define a new "standard" to fulfil the need for accurate palette exchange in this

† Image Technology Committee

‡ International Standards Organisation Technical Committee 130

proposed solution. For this to be successful, the colour observing conditions first need to be defined and then subsequently fixed. For all viewing tasks (both surface and screen), it is proposed that an illuminant D65 simulator be used. When examining surface colours, the D65 simulator will typically be housed in a special purpose viewing cabinet with adjustable luminance level control and having walls painted a neutral grey colour. (Thus, the viewing geometry, background and luminance level can be fixed.) Illuminant D65 was chosen because it corresponds to average daylight conditions and it is frequently used in the textile trade, as specified in [BSI67a].

Each colour is to be represented in essence by XYZ values. These must correspond to the readings obtained from *one* specific instrument to be used throughout and measured under a D65 simulator and 2° observer conditions. If dye recipes are predicted for a particular colour, this information (describing the dyes and their concentrations used) needs to be recorded as reference for future fabric dying. In such cases, a reflectance curve may be generated or alternatively this may come from the external measurement of physical samples. (These data may later be used for assessing colour constancy properties.) Such data should also be recorded as part of the colour record structure. Information describing its name and creation date may also be present, but these can be considered optional.

For maximum data portability, flexibility and simplicity, the *external* representation (i.e. that which is communicated) of a colour is to be ASCII text. This format has the advantage of being easy to interpret or edit by humans and also makes it convenient for incorporation into electronic mail messages. The disadvantage is the increased storage requirement over a binary representation (however, since palettes typically contain few colours, this is not really an issue). Each field is to be presented on a line tagged with a prefix to indicate its type. Palettes are represented as a list of colours formed by concatenating several individual colour records. An example colour record (with tags highlighted) is shown in Figure 5.3. As revealed by the interviews held with designers (see Chapter 3), the perceived "mood" of a palette is greatly affected by its spatial arrangement and therefore making this constant would eliminate any opportunity for misinterpretation. On the screen, colour palettes are to be presented in fixed geometry arrays of 6 × 4 colour cells, each cell having an aspect ratio of approximately 4:3. Although initially of this size, it is desirable that the user may be allowed to resize the palette area since designers often like to experiment with different arrangements. It is, however, important that the palette is communicated and *initially* represented in a fixed format. (If it is viewed incorrectly, colours are likely to be perceived differently.) The palette should initially be presented on a grey background (corresponding to the grey of the viewing cabinet) with the option of switching to white or black backgrounds as necessary.

Figure 5.3: Sample Format of a Colour Record

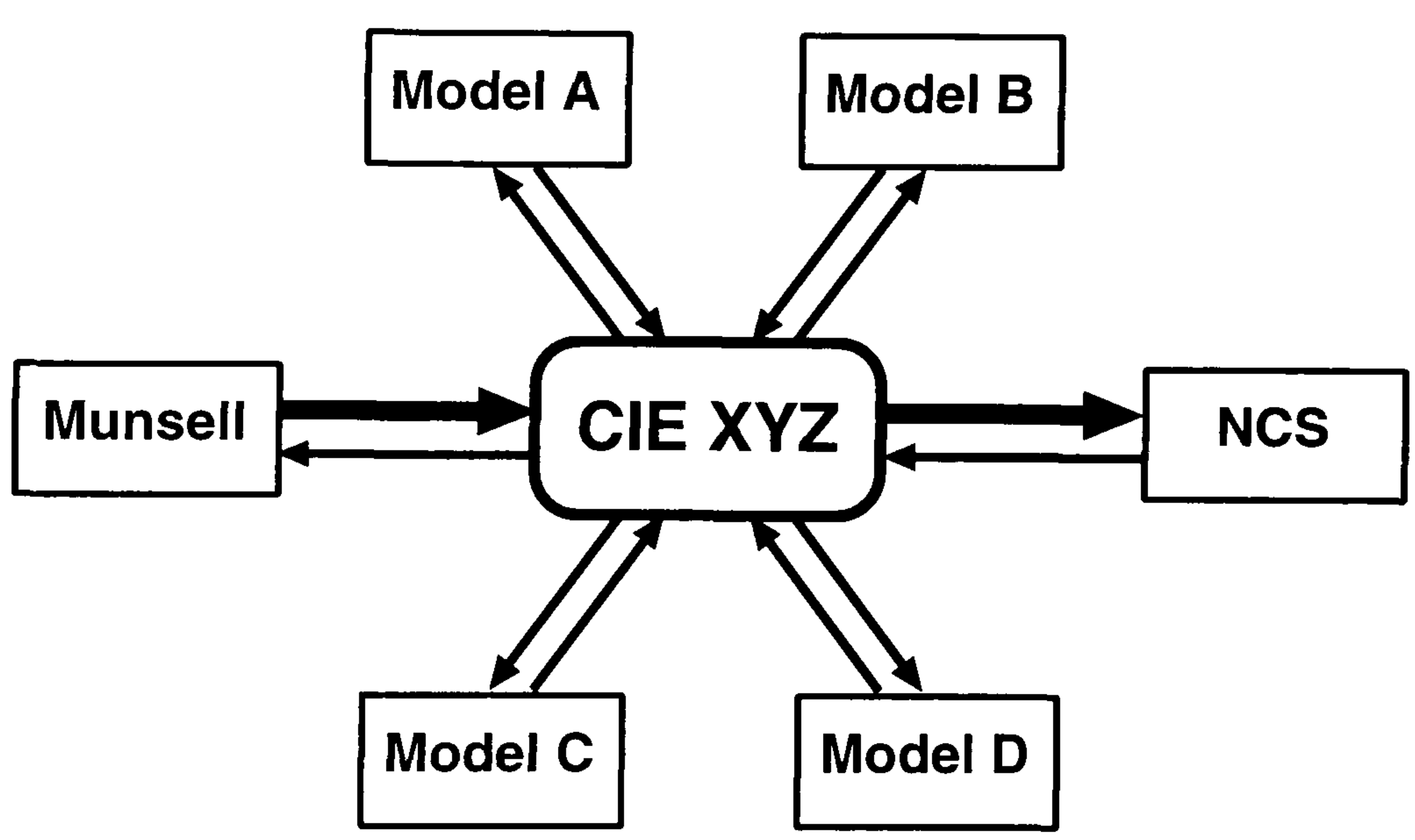
```
code: 13/ROBERT
xyzms: 9.718 11.550 5.861

recipe: 1
reflectance: 5.36 3.95 3.76 4.61 10.23 13.77 12.11 11.99
        11.31 11.43 10.66 9.11 9.95 21.09 45.34 63.08
dye-1: TERASIL PINK X-2G
dye-2: TERASIL BLUE 219 RE
dye-3: SAMARON YELLOW 6GSL P
conc: 5.848 2.924 16.32
end-recipe:

recipe: 2
reflectance: 6.40 4.66 4.35 5.07 8.68 10.34 11.45 12.67
        13.12 11.13 10.13 8.61 9.40 20.16 44.64 63.73
dye-1: TERASIL BLUE 219 RE
dye-2: PALANIL BR RED P-4GF
dye-3: SAMARON YELLOW 6GSL P
conc: 3.188 7.485 10.26
end-recipe:

illuminant: user D65
created: Wed Jan 16 13:34:39 1991
palette: lutchi.dyed.pal
xyzmonitor: 8.299 10.064 4.480

###
```

5.3.3 Colour Selection

There are, as already stated, numerous disparate colour systems currently in use by industry. The amount of time and effort already invested into these systems means that there is a great resistance to change. Therefore, rather than produce yet another "universal system" (which is unlikely to gain universal acceptance), it is more appropriate to integrate several of the more popular colour order systems and provide for interrelation of colours between these systems. This necessitates the derivation of mathematical mappings between each models' own attributes and some device independent notation, such as CIE XYZ [Rhod90a]. Making these mappings bidirectional means that it is possible to interrelate colour systems via XYZ and thus communicate colours between users of these systems. The CIE XYZ system is used as a central hub, shown in Figure 5.4, for colour conversion. For example, converting a colour represented using the Munsell system to its equivalent in NCS involves the following two mappings:

1. Munsell (H,V,C) $\rightarrow$ CIE (X,Y,Z) (*forward mapping*)
2. CIE (X,Y,Z) $\rightarrow$ NCS (Φ, s, c) (*reverse mapping*)

Figure 5.4: Interrelation of Colour Systems via CIE XYZ



Although, in principle, any device independent colour system could be used in place of XYZ, this system is the one most frequently used to define other colour standards. However, other work has been done to directly interrelate colour order systems such as NCS and CIELAB [Dere91a], NCS and Munsell [Bill87a] and NCS and DIN with OSA-UCS [Smit92a]. When interconverting colour between different systems, care should be taken over how each colour system is defined. In particular, discrepancies can arise due to dissimilar viewing conditions being used (e.g. illuminant or surface versus screen media), variations in measurement conditions (e.g. geometry, the inclusion or exclusion of the specular component) and instrumental error (unavoidable). The solution proposed here is, where the colour system is based on measured physical samples, to first transform the data from surface to screen conditions (possibly also involving a change in illuminant and viewing geometry). This may be accomplished using the four-stage transform described earlier. Furthermore, the original measurements should be made using specular exclude conditions (so as to avoid gloss surface reflections).

5.3.4 User Interface Requirements

Equally important as colour fidelity are the issues of how colour is represented on the screen and further manipulated within a computer-based design system. If the display format is not carefully controlled, it is likely that some of the colours will not be perceived "correctly" [Trav91a], thus negating any efforts to achieve WYSIWYG colour. Allowing ambient light to fall on the screen will cause colours to become desaturated and so should be minimised. (The ideal viewing environment would be a darkened room, but this is not always practical.) The perception of colour is influenced by the size, shape and edge quality of the displayed object. Edge quality affects the contrast between an area and its surround or any adjacent colour; this contrast is higher for sharp edges. In particular, the colour surrounding a target shade can result in undesirable colour contrast effects (see §2.2.3) which completely change its perceived appearance. This can be minimised by using a fixed neutral grey background for all the displayed colour areas. Colour contrast phenomena are frequently overlooked by user interface designers who are often tempted to use a thin black border around colour patches to enhance edges (in order to make objects stand out). It is suggested that such borders only be used for two specific purposes:-

(1) *indicating out of gamut colours* — this is acceptable since the displayed colour can only be, at best, an approximation to the target colour and it is desirable that the user be made aware when colours are "wrong".

(2) *highlighting selected colours* — this can only be justified where the highlighted colour is a coarse representation of the desired colour, e.g. when showing the *nearest* colour within a colour space, or where another non-highlighted copy is to be used for colour judgement. Alternatively, this use can be permitted if no colour judgement is being made of an object by the user. An example of this might be where colours have already been chosen and the user wishes

to spatially arrange them in some order.

In conventional CAD systems, colour is treated as an attribute and is therefore difficult to manipulate separately. (It becomes too closely linked with the actual design or image, thus making it difficult to change.) Instead, it is proposed that colour itself is treated as an independent object. This representation makes it easier for the user to move colour information between applications and also has the advantage of making it possible to show the same design in several colourways (since form and colour are no longer tightly bound). Additionally, several colour objects may be grouped into single palette objects. Both palette and colour objects may then be communicated between application programs within the CAD system using whatever paradigm is appropriate to the graphical user interface environment being used (e.g. "cut and paste" or "drag and drop"). By using a particular system's own standard inter-application communication mechanism means that, because the external object representation is textual, communication of colour information should be possible even with those applications not understanding its meaning. An example of where this might be useful is after creating a colour palette, certain colours may be copied from its window and pasted into an e-mail program's window (thus forming part of the transmitted document itself). All the recipient then has to do is to copy the (textual) colour information from his/her mail reading application and into another colour palette window running on the remote system.

To support WYSIWYG colour palette creation, a number of "colour management" tools are required in addition to those found in a conventional CAD system. The core tools which are considered essential to any such system are listed below:-

- palette area — including the ability to move or rearrange, edit (duplicate, destroy) and view palette colours (in a fixed format).
- colour selection and adjustment via standard colour notation systems.
- file management — for archival and communication of colour data. This would be useful for fashion palette designers who often base new palettes on past seasons' shades.
- visualisation of "colour effects" such as simultaneous colour contrast, colour harmony, colour constancy and metamerism.

- calibration — involves the display and (possibly manual) measurement of screen colours to maintain correct colour fidelity over time.

Additional tools may also be desirable if further control is desired over the production of a design:-

- colour tolerance — it is useful to visualise what the effect of a particular production tolerance setting will mean in terms of batch colour variation.
- recipe prediction — for textile designers, being able to directly output recipes which can be sent directly to the dye house can save time and money.
- hardcopy — printed output is often useful as a means of communicating colour or design ideas, particularly in the early stages of design.
- colour measurement — where an existing colour sample exists which is to be utilised as part of a colour palette or design, it is desirable to be able to directly measure this for immediate use. The alternative to this would be tedious manual colour matching between viewing cabinet and screen. Matching may also be necessary for certain special cases, e.g. when the physical samples are too small to measure or where various media (paint, ink, textiles) samples are involved.

The above tools are described in more detail in the next chapter.

5.4 SUMMARY

In this chapter, an outline solution to the problems of colour fidelity and colour communication for textile CAD system users has been proposed. It was argued that such a system should employ WYSIWYG colour throughout in order to attain the high colour fidelity that is demanded by the designers and their customers. Various techniques for achieving this were suggested and it was further argued that a good *visual* match between multiple media or involving dissimilar viewing conditions required the use of both a device calibration model and a colour appearance model. It was stressed what compromises were necessary due to the limitations of colour gamut inherent to modern computer displays and hardcopy devices. The advantages of electronic colour selection and specification over traditional methods were also mentioned; in particular how this might enable the accurate exchange of colour information. A description of the sort of data required to represent a colour was given and, in the absence of any existing standard, an external format was suggested for this information. Finally, some additional tools for colour management were given together with guidelines for the representation of colour within CAD systems. Throughout this discussion, only an abstract system has been mentioned. A real implementation of these ideas is discussed in the next chapter.

Chapter Six
System Implementation

CHAPTER SIX: SYSTEM IMPLEMENTATION

6.1 INTRODUCTION

In the preceding chapter, an outline solution to the problems of colour fidelity and colour communication faced by designers was presented. This chapter reports on how those ideas were put into practice in the form of a demonstrator called *ColourTalk*. Much of this work was carried out as part of a research project funded jointly by the SERC and DTI Information Engineering Advanced Technology Programme (IEATP) entitled "Colour Appearance Research for Interactive Systems Management and Applications" (CARISMA). The project ran from February 1990 for three years and was a collaborative venture between the textile manufacturer Coats Viyella, Crosfield Electronics and the LUTCHI Research Centre. The development of the ColourTalk system was carried out in two stages, beginning first with a prototype system capable of illustrating the basic concepts. This was later refined and extended to form part of the CARISMA project final demonstrator.

In this chapter, details are given as to how display fidelity was realised and how mathematical mappings were derived to interrelate various colour notation systems. Finally, the prototype and final ColourTalk systems are described and related to the requirements of the designers (given in Chapter 3).

6.2 COLOUR FIDELITY

In the last chapter (§5.2.1 and §5.3.1), it was argued that the problem of colour fidelity could be solved through device characterisation and the application of a colour appearance model. A discussion of the use of the colour appearance model as part of the FST was detailed in §5.3.1.2. In this section, display device characterisation is looked at in detail. Being able to accurately display colours on a monitor screen is of fundamental importance to any WYSIWYG CAD system. Monitor characterisation is necessary to overcome device dependency and, as already mentioned, consists of two stages: device calibration and modelling.

6.2.1 Monitor Calibration

For this work, a Barco Calibrator monitor was used. This is the first of a new generation of "intelligent" monitors, capable of maintaining both short-term and long-term colour stability [Barc90a]. This monitor compensates for short-term effects by constantly sampling and correcting the RGB gun voltages that drive the CRT. At the same time, it also gradually increases these voltages to maintain screen luminance (which would otherwise fall due to the decay of the screen phosphors) and hence ensures long-term stability. The monitor includes an external light sensor (capable of measuring only luminance, and not chromaticity) which is used by the Calibrator's internal microprocessor to control a calibration sequence. Essentially, this makes a series of external measurements with the sensor of the individual and combined RGB guns and subsequently adjusts various internal parameters until the readings correspond to values it has stored in its memory. (These reference values are determined in the factory and relate to the measurements of a more precise master instrument.)

It was found that this calibration stage alone was not sufficient: although it corrected for external differences in the light *output*, there was no consideration for the *input* signal. Different video sources (i.e. computer graphics hardware) produce slightly different output voltage ranges. (One obvious manifestation of this problem was that the screen "black" did not appear as dark as the surround as a result of the residual signal.) Consequently, a second calibration stage was devised to correct for this. This second stage was performed under the control of the host computer system, by means of a serial communications link to the monitor's microprocessor. A light (100% intensity) and a dark (40% intensity†) patch was generated and measured for both internal and external (to the monitor) video sources. Corrections were made to the background (brightness) and picture (contrast) settings until the readings from the light sensor indicated that these two sources were the same.

Thus, calibration of this monitor was a two-stage process, fully controlled by the host computer. Such a calibration would typically need to be done once each day in order to maintain colour fidelity. A study of the performance of three such monitors [Luo91a] indicated that colour repeatability (around 0.7 CMC(1:1) colour different units) and reproducibility was highly satisfactory.

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† 40% was arbitrarily chosen because *very* dark colours would incur more instrumental noise in their measurement.

6.2.2 Monitor Characterisation Model

Generating colours on a CRT monitor for given set of CIE tristimulus values requires some sort of characterisation model. (For small numbers of colours, a simple trial-and-error method can be used.) This is done by first measuring various colours (defined in terms of RGB DAC values) and then deriving a mathematical model to fit these data. The model should then be able to predict what RGB values are required to reproduce a given colour. There are several methods available for doing this and these have been studied by Post and Calhoun [Post89a]. All the models looked at, except for PLVC, assumed gun independency† and it was concluded that the PLVC model [Farl80a, Ston88a] (piecewise linear interpolation assuming *variable* chromaticity coordinates) performed the best of the seven models investigated. PLVC requires the measurement of a number of RGB colour combinations in the form of a device space characterisation cube and uses interpolation to locate intermediate colours. To be effective, this method generally involves measuring *large* numbers of colours which takes considerable time and requires storage of a large database of measured points. A later study, as part of the work described here [Luo91a], has demonstrated that both the PLCC (piecewise linear interpolation assuming *constant* chromaticity coordinates) and LOG-LOG2 [Cowa83a] models could be made to out-perform‡ PLVC and the other models mentioned in Post's study provided that the DAC level distribution was carefully chosen. (Post had selected equally spaced DAC values, however it was shown that including more points in the lower end significantly improved the model's performance for darker colours.)

Both PLCC and LOG-LOG2 models were used in this work, and these are now described. The relationship between RGB and XYZ can be written:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_r/y_r & x_g/y_g & x_b/y_b \\ 1 & 1 & 1 \\ z_r/y_r & z_g/y_g & z_b/y_b \end{bmatrix} \begin{bmatrix} R_L \\ G_L \\ B_L \end{bmatrix}$$

where (x_i, y_i, z_i) define each of the R, G and B gun chromaticities and (R_L, G_L, B_L) represent the luminances of each gun. This can also be written as $T = CY$, and the inverse mapping is then $Y = C^{-1}T$. Where

† i.e. there is no interaction between the red, green and blue guns in the CRT.

‡ The predictive performance using a uniform data set was found to be 0.83 ΔE units for PLCC, 0.90 for LOG-LOG2 and 1.09 for the PLVC model with an equal DAC distribution.

the PLCC, LOG-LOG2 and other models differ is in their calculation of $R_L G_L B_L$ from the RGB DAC values.

The PLCC model is one of the easiest to implement and can, using a proper interval of DAC values, yield very good results. PLCC assumes that gun luminance varies linearly between the measured points. Given a set of such points (ranging from zero to the maximum DAC value), any value in between is calculated by simple linear interpolation between two neighbouring points. The implementation used here utilised eighteen equally spaced DAC points per gun. Using more points increases measurement time and does not improve the results by very much. (There is a trade off between measurement time and accuracy.) The performance of this model is given in [Luo91a].

LOG-LOG2 defines a second-order logarithmic regression model for each gun of the form:

$$\log T = c_1 + c_2 \log D + c_3 (\log D)^2$$

where T is the luminance and D is the normalised DAC value. The coefficients c_i are computed for each channel using a Quasi-Newton optimisation technique [Gill82a] for a number of DAC levels (whose luminance was measured). In this method, the root mean square difference between measured and predicted luminance is iteratively minimised.

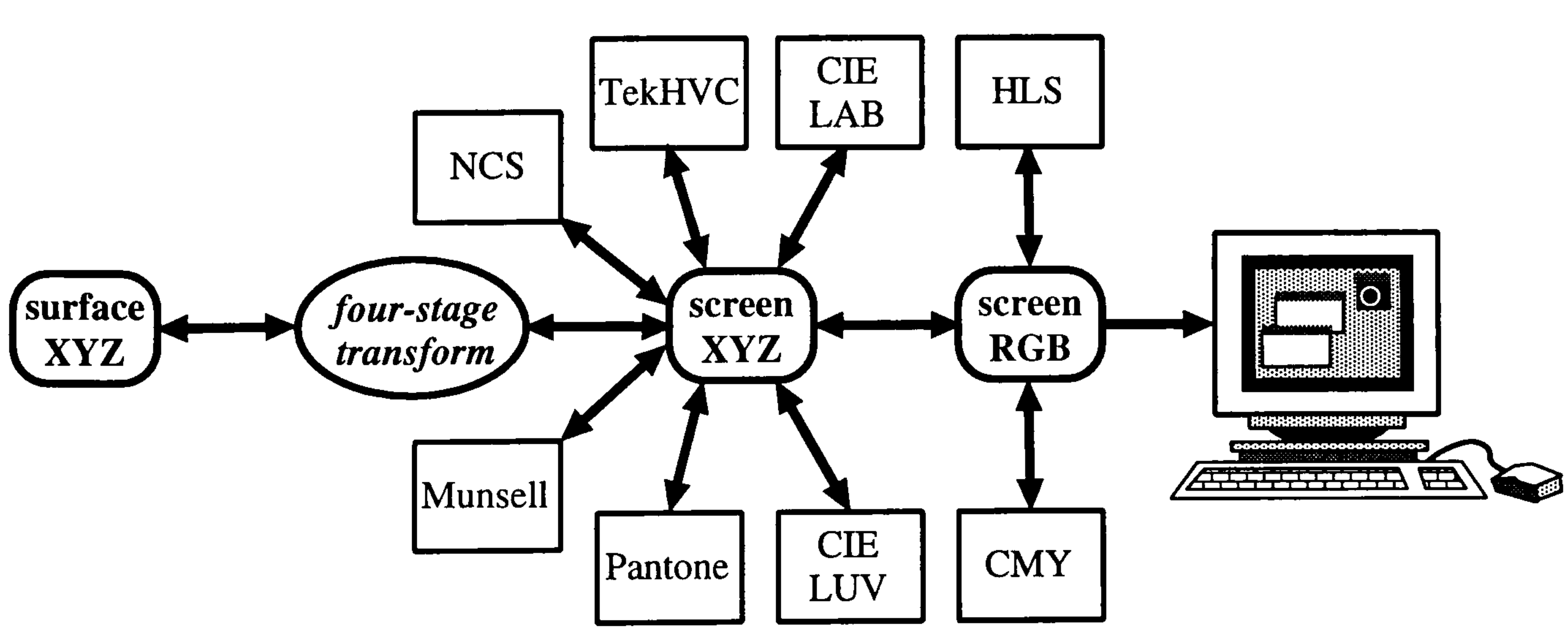
6.2.3 Colour Measurement

Color fidelity is dependent upon the accuracy and repeatability of the colour measurement equipment used for characterisation. All colorimetric data used in this work were based on the measurements of a *single* telespectroradiometer which was in turn calibrated using a lamp traceable to the NPL standard. However, it should be noted that different instruments (even those of the same type) "see" colours differently — this effect is known as *instrument metamerism* — and so it would be unwise to expect that two displays should match if each was characterised using a separate instrument. Another source of concern is screen uniformity (or lack thereof). It is an acknowledged problem that colour and luminance level are not constant across the area of a CRT (for the Barco Calibrator used, a luminance variation of around 15% was measured). It was, therefore, decided to conduct all measurement at the *centre* of the screen where the luminance level is generally the highest.

6.3 COLOUR MODELS

A colour space may be defined by some mathematical function (e.g. CIELUV and CIELAB are mathematical transformations of CIE XYZ space) or be based upon the measured colour of physical samples (colour order systems). In either case, it is often desirable to be able to relate colours to the CIE XYZ standard, so that this information may subsequently be used to reproduce the colours on screen, printed media, etc. Colour measurement instruments typically describe colours in terms of tristimulus values. In order to locate arbitrarily chosen colours (which have been measured) within a particular colour space, it is necessary to utilise an "XYZ to colour model" mapping. Having bidirectional mappings between several models and XYZ (or any other device independent colour notation, such as CIELUV) enables colours from one colour notation system to be related to the same, or similar, colours in a different colour system. The concept of using XYZ as a *central hub* for such interrelation tasks and for visualisation of colour spaces using a display is illustrated in Figure 6.1. This also shows how measured surface XYZ data are transformed to screen XYZ via the FST.

Figure 6.1: Interrelating Colour Systems via XYZ



The principal aims in implementing various colour models can be summarised as follows:-

(1) to describe various colour notation systems in terms of CIE XYZ so that they may be used

interactively as part of a computer-based system for colour selection [Jobl78a, Rhod90a].

(2) to interrelate different colour systems via a CIE XYZ central hub (rather than having many bidirectional mappings between each individual model and every other model considered) [Smit90a] for colour communication tasks.

Additionally, colour spaces may also be applied to various "computational" tasks, usually by providing a means of *interpolating* between colours. Such applications include colour coding (including *nominal*† and *ordinal*‡ coding [MacD90b]), the modelling of non-visual data (e.g. medical or satellite imaging, the presentation of demographic data [Rhei90a]), blending or fading between two images and performing photorealistic simulation (e.g. using Gouraud shading [Gour71a]).

There are numerous colour systems in use today — far too many to enumerate. Therefore, to make this work feasible, only those systems in common use were studied. These were deemed to be: RGB, CMY, HLS, Pantone, CIELAB, CIELUV, Munsell, NCS, TekHVC, DIN, and OSA. The RGB, CMY and HLS models are device dependent (that is, relating to *one* particular item of colour output equipment) and are, due to their simplicity and ease of implementation, the most frequently used means of describing colour in conventional computer systems. Pantone, Munsell, NCS, DIN and OSA all exist as physical standards and so are often used in this form for non-CAD work. CIELAB and CIELUV are commonly used for colour difference and colour specification tasks. The TekHVC model is employed by the Tektronix TekColor matching system which is available for low-end DTP systems.

6.3.1 Mathematical Mappings

For each of the models mentioned, bidirectional mathematical mappings were derived between each model's attributes and CIE XYZ. In the following section, these are described in detail. A number of methods already exist for many of these mappings (and also for transforming data *directly* between certain colour systems), although the list is not complete. Despite this, a major obstacle remains to be overcome:

† *nominal coding* — each "state" is represented using a different colour, e.g. coding each aeroplane uniquely for air traffic control.

‡ *ordinal coding* — colour is used to represent one or more variables (particularly useful if the x- and y-axes are already being used to represent other variables, such as position). E.g. using lightness to represent the magnitude of a reading over a two-dimensional sensor array.

the data defining these systems are frequently specified for different viewing conditions and simple colorimetric interrelation, by definition, will *not* work.

RGB, CMY and HLS

The process of interconverting RGB and XYZ was discussed in §6.2. CMY can be trivially derived from RGB using:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

This assumes that the RGB and CMY values have all been normalised to a scale of 0 to 1. For the HLS model, the sample implementation to and from RGB space given in [Fole84a] was used. Thus, CMY and HLS can be related to XYZ *via* RGB.

Pantone

The Pantone Matching System† is used internationally by the publishing, printing and packaging colour industries. This system actually exists in various forms according to the media used for its reproduction (e.g. coated and uncoated paper), together with printing ink mixing formulas. For this work, the "Color Formula Guide 747XR" was used [PANT90a]. This is presented in strips of up to nine colours per page on coated (i.e. glossy) paper, each colour having a name or code written beneath it. Each page generally consists of colours having a broadly similar hue, although there are some "special" pages which contain fluorescent and metallic samples. A database of 751 XYZ values for most of these colours, measured using illuminant D50 and 2° observer surface colour conditions, was acquired from the manufacturer. These then had to be transformed to D65, 2° screen viewing conditions using the four-stage transform mentioned in §5.3.1.2. This new database enabled a named Pantone colour to be expressed in terms of XYZ values, and hence reproduced on screen or in print.

The reverse mapping had to be implemented somewhat differently to most other models. This is because Pantone colours do not describe a colour space (there are no Pantone attributes, other than a one

† PANTONE and PANTONE MATCHING SYSTEM are trademarks of Pantone Inc.

dimensional colour code) and, as such, this makes it impossible to interpolate: there is no way of describing intermediate hues without recourse to another colour space. Therefore, given an arbitrary set of XYZ values, the *closest* Pantone shade must be found. The definition of "closest" used here meant locating the colour having the minimum absolute CMC (1:1) total colour difference from the target. In order to do this, the entire Pantone database was exhaustively searched. (A more elaborate scheme might be to partition a colour space into N regions and maintain a list of which Pantone colours belonged to which subspace. A given colour could then be more rapidly located by searching only those regions neighbouring the target. In practice, this proved unnecessary as a search of the entire database took well under a second.) Because the number of available colours in this system is relatively small and also because of the perceptually uneven distribution of Pantone colours, the closest located colour could actually be off by more that ten CMC(1:1) ΔE units — which is by no means satisfactory!

As a cautionary note, a visual comparison was made between colours from two sets of uncoated physical samples, each produced by a different licenced manufacturer but both sets supposedly adhering to the same "Pantone standard". This simple test, although not particularly rigorous, demonstrated that colour fidelity between such "similar" systems was unlikely to be very good. This did not bode well for the successful interrelation of Pantone with other (different) colour notation systems.

CIELAB and CIELUV

Both CIELAB and CIELUV are fully described mathematically [CIE85a] and are transforms of the original CIE XYZ space (each transform producing a uniform colour space). CIELUV (L^*, u^*, v^*) can be written as follows:

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 & \text{if } \frac{Y}{Y_n} > 0.008856, \\ 903.3\,\frac{Y}{Y_n} & \text{if } \frac{Y}{Y_n} \le 0.008856, \end{cases}$$

$$u^* = 13L^*(u' - u'_n),$$

$$v^* = 13L^*(v' - v'_n).$$

where (Y, u', v') and (Y_n, u'_n, v'_n) define the target and reference white colours respectively and

$$u' = 4X/(X + 15Y + 3Z) = 4x/(-2x + 12y + 3),$$

$$v' = 9Y/(X + 15Y + 3Z) = 9y/(-2x + 12y + 3).$$

(Hence, $x = 9u'/(6u' - 16v' + 12)$ and $y = 4v'/(6u' - 16v' + 12)$.) From these, the polar coordinates h_{uv} and C^*_{uv} can be derived:

$$h_{uv} = \tan^{-1}(v^*/u^*),$$

$$C^*_{uv} = \sqrt{u^{*2} + v^{*2}}.$$

The polar representation is, typically, more useful for computer graphics (e.g. in choosing complementary hues for maximum contrast) and these attributes have greater perceptual meaning than u' and v' when used for colour selection. Inverting these equations makes it also possible to find (u', v', Y) (and hence XYZ) given (L^*, u^*, v^*):

$$u' = \frac{u^*}{13L^*} + u'_n,$$

$$v' = \frac{v^*}{13L^*} + v'_n,$$

$$Y = \begin{cases} \dfrac{Y_n f_n}{7.78} & \text{if } f_n \le 0.06896, \\ Y_n(f_n + 16/116)^3 & \textit{otherwise} \end{cases}$$

where $f_n = L^*/116$.

The CIELAB colour space (L^*, a^*, b^*) uses the same definition for L^*, and further defines a^* and b^* as follows:

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right],$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right],$$

where (X_n, Y_n, Z_n) define the reference white. If any of the ratios X/X_n, Y/Y_n or Z/Z_n (which we will call F) are less than or equal to 0.008856, it is replaced by

$$7.787F + \frac{16}{116}.$$

Again, polar coordinates can be derived using:

$$h_{ab} = \tan^{-1}(b^*/a^*),$$

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}}.$$

This may be inverted in order to find CIE XYZ as follows:

$$f_0 = \frac{L^*}{116} + \frac{a^*}{500},$$

$$f_1 = \frac{L^*}{116}$$

$$f_2 = \frac{L^*}{116} - \frac{b^*}{200}$$

Then,

$$\text{if } f_i \leq 0.06896 \textit{ then } f_i' = f_i / 7.787$$

$$\textit{else } f_i' = (f_i + 0.1379)^3.$$

Finally,

$$X = X_n f_0', \; Y = Y_n f_1', \; Z = Z_n f_2'$$

Munsell Colour System

The Munsell system is based on the *Munsell Book of Color* (see §2.6.3). It consists of coloured chips which were intended to have equal visual spacing between each of its Hue (H), Value (V) and Chroma (C) attributes. Work was done to smooth these points and a set of CIE XYZ values were subsequently made available [Newh43a]. These "aim points", together with [Kell43a], were used to derive a Munsell-to-XYZ mapping. (The data had first to be transformed using the FST from illuminant C, 2° observer, surface conditions to those of the D65 simulator, 2° observer, screen conditions.) An interpolation technique similar to that of [Lam85a] was implemented to locate the chromaticity for a given target (x, y). Y was calculated directly from V using the following polynomial approximation:

$$Y = 0.37063 + V(-0.45517 + V(0.48153 + 0.058011V))$$

which was obtained by regression fitting (V, transformed Y) data points. The interpolation algorithm uses the eight neighbouring points forming a cube around the target and taken from the set of aim points (some of these eight points are necessarily duplicated in the case of boundary or near-neutral colours). This aim point database consists of (x, y) data points for 2.5 unit steps of Hue (i.e. 40 hues), two unit steps of Chroma and one unit step of Value (although there are no definitions for some of the higher Chroma values). The initial problem of three-dimensional interpolation of the (x, y) data is reduced to two-dimensions and finally to just one dimension using simple linear interpolation at each stage. For a given HVC (where H here specifies an angle in degrees) and aim point database M(H,V,C), the eight points (ignoring Hue wrap-around) are:

$$P_1 = M(H_i, V_i, C_i), \qquad P_2 = M(H_i, V_i, C_i + 2)$$

$$P_3 = M(H_i, V_i + 1, C_i), \qquad P_4 = M(H_i, V_i + 1, C_i + 2)$$

$$P_5 = M(H_i + 2.5, V_i, C_i), \qquad P_6 = M(H_i + 2.5, V_i, C_i + 2)$$

$$P_7 = M(H_i + 2.5, V_i + 1, C_i), \quad P_8 = M(H_i + 2.5, V_i + 1, C_i + 2)$$

where

$$H_i = 2.5\left\lfloor \frac{H/3.6}{2.5} \right\rfloor, \qquad V_i = \lfloor V \rfloor, \quad C_i = 2\left\lfloor \frac{C}{2} \right\rfloor$$

Where $\lfloor x \rfloor$ represents the rounded down (or floor) value of x. Given

$$\Delta H = H/3.6 - H_i, \qquad \Delta V = V - V_i, \qquad \Delta C = C - C_i$$

the interpolation proceeds as follows:

$$q_1 = p_1 + \Delta C(p_2 - p_1),\ q_2 = p_3 + \Delta C(p_4 - p_4)$$

$$q_3 = p_5 + \Delta C(p_6 - p_5),\ q_4 = p_7 + \Delta C(p_8 - p_7)$$

These four points are then reduced to two as follows:

$$r_1 = q_1 + \Delta V(q_2 - q_1),\quad r_2 = q_3 + \Delta V(q_4 - q_3)$$

Finally, the target point is found:

$$t = r_1 + \Delta H(r_2 - r_1)$$

This same method is used to calculate both x and y and the (x, y, Y) values thus obtained can be used to compute (X, Y, Z).

The reverse Munsell mapping (i.e. XYZ to HVC) uses an iterative approach relying on the forward mapping. (A number of other more elaborate schemes also exist, such as [Rhei60a] and [Simo87a].) The algorithm begins by calculating an initial estimate of HVC using the CIELAB coordinates of the target point:

$$H_0 = h_{ab} + 130°$$

$$V_0 = 0.8494 + \log_{10} Y(1.7017 + \log_{10} Y(1.7121 - \log_{10} Y(1.3081 - \log_{10} Y(0.86223 - 0.14095 \log_{10} Y))))$$

$$C_0 = C^*_{ab} / 6.25$$

(Again, the relation between V and Y was found empirically by fitting data points.)

During each cycle of the iteration, XYZ values for the current HVC are computed. If this mapping fails, it is assumed to be because Chroma is out of table range and so this attribute is decreased until the point lies back in range. Otherwise, the CIELAB coordinates for the current XYZ are computed and the difference from the target point's $L^* C^*_{ab} h_{ab}$ calculated. If this difference is sufficiently small ($|\Delta L^*|$, $|\Delta C^*_{ab}|$ and $|\Delta h_{ab}|$ all < 0.0001 units) then the current value is considered to be "close enough." Otherwise, a correction is applied as follows:

$$H_{i+1} = H_i + \Delta h_{ab}$$

$$V_{i+1} = V_i + \Delta L^* / 10$$

$$C_{i+1} = C_i + \Delta C^*_{ab} / 6.25$$

and the process is repeated until a maximum of fifty iterations have been tried. (Typically, this was only found to happen for colours that were outside the Munsell table range.) The algorithm also included further refinements for boundary cases which are, for simplicity, not discussed here.

Natural Colour System (NCS)

NCS exists in both an atlas form [SIS79a], containing 1412 colour samples and also as a set of *notations* [SIS72a]. Samples for the atlas system have been measured in terms of tristimulus values [SIS82a] and interpolation was subsequently used to provide around 16,000 notations and their corresponding tristimulus values [SIS83a]. The latter source of data (containing points spaced at five unit intervals for blackness and chromaticness and five percent hue steps for each quadrant — i.e. eighty hues) was used in order to map colours to and from the CIE system. (These data had been obtained originally by measurement under illuminant C, 2° observer surface conditions and once again had to be transformed to 2°, D65 screen conditions using the FST.) Data for the neutral points were obtained from Y values given in [SIS72a]. For each of the Y values (100, 76.36, 58.95, 45.58, 35, 26.42, 19.31, 13.33, 8.42 and 0), the chromaticity of the (real) light source was used to calculate the XYZ for each ten-unit interval of NCS blackness.

The forward mapping (i.e. NCS to CIE coordinates) uses an interpolation method and is outlined as follows. Before beginning, a test is made to see if the target colour is out of NCS table range, in which case: blackness (s) + chromaticness (c) > 100. Also, for neutral colours (i.e. c = 0 or red + yellow + green + blue = 0), the chromaticity is taken to be that of the light source used (D65 simulator) and a simple relation (given in [SIS79a]) can be used to calculate Y:

$$v = (100 - s) / 100$$

$$Y = 56v / (1.56 - v)$$

where v is lightness (being the numeric reverse scale of blackness). For all other cases, the first stage is to convert the red, yellow, green and blue percentages into a hue angle (ϕ) in the range 0-400. (Each NCS hue primary is separated by 100 units.) Next, the hue type is analysed in order to choose appropriate points for interpolation. Five "special cases" have to be dealt with: near white, near black, near neutral, near c=100, and near lower boundary. These are illustrated in Figure 6.2. In some cases, certain interpolation points have to be used more than once — in particular, the neutral points. (Note that the interpolation is three-dimensional: similarly positioned points for the two hue leaves either side of the target point are considered.)

Once the eight interpolation points have been established, *trilinear interpolation* is used (similar to that given on page 267 of [Ston88a]), as shown below, for each X, Y, Z attribute:

$$\begin{aligned}\text{X, Y or Z} = {} & p_0 + \Delta\phi(p_1 - p_0) + \Delta s(p_2 - p_0) + \Delta c(p_4 - p_0) + \\ & \Delta s \Delta c(p_6 - p_2 - p_4 + p_0) + \\ & \Delta\phi \Delta c(p_5 - p_1 - p_4 + p_0) + \\ & \Delta\phi \Delta s(p_3 - p_1 - p_2 + p_0) + \\ & \Delta\phi \Delta s \Delta c(p_7 - p_3 - p_5 + p_1 - p_6 + p_2 + p_4 - p_0)\end{aligned}$$

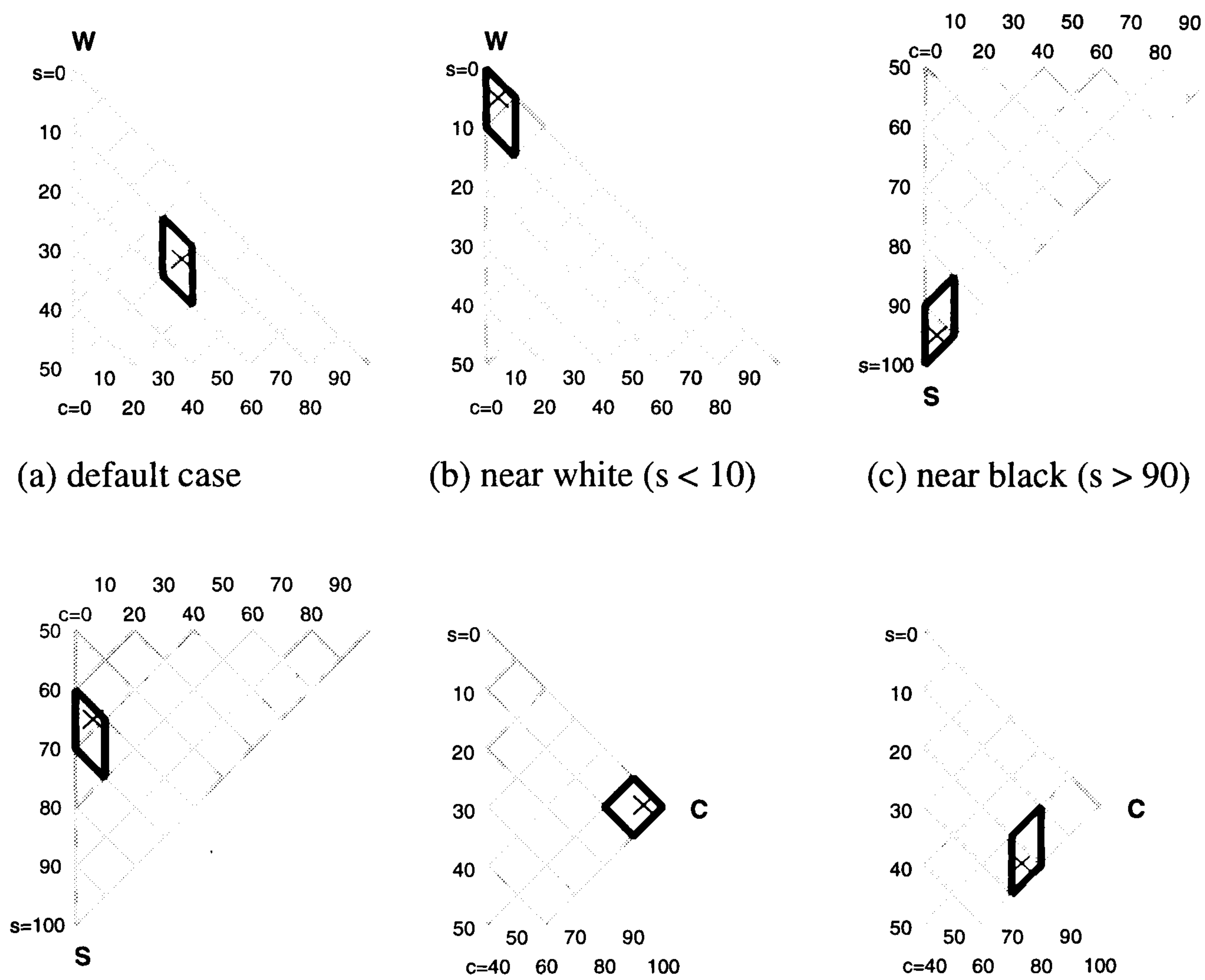
where p_i are the interpolation points used for X, Y or Z (as appropriate) and $\Delta\phi$, Δs, Δc represent the differences between the target point and the nearest (ϕ, s, c) aim point in the NCS database which is numerically less than or equal to the target.

The reverse NCS mapping followed a similar route to the inverse Munsell mapping, but with an increased complexity. First, CIELAB L^*, C^*_{ab}, h_{ab} are computed and an initial estimate for NCS hue is found:

$$\phi_{initial} = -34.504 + h_{ab}(1.121 + h_{ab}(5.931\times10^{-3} - h_{ab}(2.9671\times10^{-5})))$$

The initial values for s and c are fixed at 25 and 50 respectively. At each successive iteration, (X, Y, Z) is computed for the current (ϕ, s, c) and this is used to find the difference from the target in terms of CIELAB ΔL^*, ΔC^*_{ab}, Δh_{ab}. Additionally, the CMC(1:1) ΔE overall colour difference is calculated (this is used to record the "best" approximation if an "exact" solution cannot ultimately be found). A solution is found if $|\Delta L^*|$, $|\Delta C^*_{ab}|$ and $|\Delta h_{ab}|$ are all less than 0.0001 units. Otherwise, a correction is made based on the ΔLCH values. If the result was found to lie outside of the NCS table range (i.e. s + c > 100) the current chromaticness value is reduced. A maximum of fifty iterations are performed (if necessary). The implementation also includes several more subtleties (not detailed here) to consider various boundary cases and to improve stability. These were all added empirically to the basic algorithm.

Figure 6.2: Interpolating NCS space (for target point X)



(a) default case (b) near white (s < 10) (c) near black (s > 90)

(d) near neutral (c < 10) (e) near c=100 (f) s + c > 90

OSA-UCS

The OSA-UCS colour order system exists as a set of 558 coloured chips but can be directly related to the CIE system [MacA74a] as now described. Given tristimulus values (x, y, Y), the luminous reflectance, Y_0, of a grey colour perceived to have an equal lightness to the target is computed:

$$Y_0 = Y(4.4934x^2 + 4.3034y^2 - 4.276xy - 1.3744x - 2.5643y + 1.8103) \tag{6.31a}$$

Next, the lightness coordinate, Λ, is found:

$$\Lambda = 5.9\left[Y_0^{1/3} - \frac{2}{3} + 0.042(Y_0 - 30)^{1/3} \right] \tag{6.31b}$$

The XYZ values of the target are used to calculate the R, G, B, primaries:

$$R = 0.7990X + 0.4194Y - 0.1648Z \tag{6.31c}$$

$$G = -0.4493X + 1.3265Y + 0.0927Z \tag{6.31d}$$

$$B = -0.1149X + 0.3394Y + 0.7170Z \tag{6.31e}$$

A factor, C, (which applies "crispening" to colour differences according to the proximity of their lightness to the 30% reflectance grey surround) is computed as follows:

$$C = \Lambda / \left[5.9 \left(Y_0^{1/3} - \frac{2}{3} \right) \right] \tag{6.31f}$$

Finally, the OSA-UCS chromaticness coordinates, (j, g), can be determined:

$$j = C(1.7R^{1/3} + 8G^{1/3} - 9.7B^{1/3}) \tag{6.31g}$$

$$g = C(-13.7R^{1/3} + 17.7G^{1/3} - 4B^{1/3}) \tag{6.31h}$$

It is also possible to derive OSA hue = $\tan^{-1}(g/j)$ and OSA chroma = $\sqrt{j^2 + g^2}$.

The forward mapping, to find XYZ for a given (Λ, j, g), uses an iterative approach devised by Dr. W.S. Yousif as part of the project† that preceded CARISMA. Equation (6.31b) given earlier can be re-written as follows:

$$5.9\Lambda + \frac{2}{3} = Y_0^{1/3} + 0.042(Y_0 - 30)^{1/3}$$

Let $k = 5.9\Lambda + \frac{2}{3}$ and $r = Y0^{1/3}$, then

$$k = r + 0.042(r^3 - 30)^{1/3}$$

$$\Rightarrow 0.042(r^3 - 30)^{1/3} = k - r$$

Cubing both sides gives

$$(0.042)^3(r^3 - 30) = (k - r)^3$$

$$\Rightarrow 1.000074088r^3 + 3k^2r - 3kr^2 - k^3 - 0.00222264 = 0$$

† DTI/SERC Alvey project entitled *Predictive Perceptual Colour Models*, (1986-1989).

The method then begins by using Newton's method‡ to find the (real) root of this polynomial [Cont83a], and hence determine Y_0 from Λ. From this, the C factor can be found using equation (6.31f). Rewriting (6.31a) in terms of X, Y, Z gives:

$$Y_0 = \frac{Y}{(X+Y+Z)^2}\left[\begin{array}{l} 4.4934X^2 + 4.3034Y^2 - 4.267XY - 1.3744X(X+Y+Z) \\ -2.5643Y(X+Y+Z) + 1.8103(X+Y+Z)^2 \end{array}\right]$$

Then, define F_1(X, Y, Z) = 0 as follows:

$$F_1(X, Y, Z) = \frac{Y_0(X+Y+Z)^2}{Y} - (4.9293X^2 + 3.5494Y^2 + 1.8103Z^2 - 4.5941XY +$$

$$4.5941XY + 2.2462XZ + 1.0563YZ) \qquad (6.31i)$$

From equations (6.31g) and (6.41h), two further functions can be obtained:

$$F_2(X, Y, Z) = \frac{j}{C} - 1.7R - 8G + 9.7B = 0 \qquad (6.31j)$$

$$F_3(X, Y, Z) = \frac{g}{C} - 13.7R - 17.6G + 4B = 0 \qquad (6.31k)$$

Equations (6.31i), (6.31j) and (6.31k) can be solved by a generalised Newton-Raphson method [Pres89a, Flet87a]. For the k^{th} iteration, this can be written:

(a) Solve $\delta^{(k)} = (\ A^{(k)}\ )^{-1} F^{(k)}$

(b) $x^{(k+1)} = x^{(k)} + \delta^{(k)}$

where

$$A = [\ \nabla F_1, \nabla F_2, \nabla F_3\ ] = \begin{bmatrix} \frac{\delta F_1}{\delta X} & \frac{\delta F_1}{\delta Y} & \frac{\delta F_1}{\delta Z} \\ \frac{\delta F_2}{\delta X} & \frac{\delta F_2}{\delta Y} & \frac{\delta F_2}{\delta Z} \\ \frac{\delta F_3}{\delta X} & \frac{\delta F_3}{\delta Y} & \frac{\delta F_3}{\delta Z} \end{bmatrix}$$

‡ Also known as the *Newton-Raphson* method.

is the 3×3 Jacobian matrix. Initial estimates, $X^{(0)}$, $Y^{(0)}$, $Z^{(0)}$ are all set identically according to the value of Λ. These are: 65 for $\Lambda \geq 3$, 40 for $0 \leq \Lambda < 3$, 25 for $-3 \leq \Lambda < 0$ or 10 for $\Lambda < -3$. Hence, values for X, Y and Z can be obtained.

TekHVC

This system, described in [Tekta, Tayl89a] is a simple transformation of the CIELUV (L^*, C^*_{uv}, h_{uv}) colour space. Its attributes (Hue, Value, Chroma) are calculated as follows:

$$Hue = h_{uv} - \theta$$

$$Value = L^*$$

$$Chroma = \frac{C^*_{uv} C_f}{13}$$

Where C_f, the chroma scaling factor, is 7.50725. The hue offset (θ) is used to assign 0° to the "best red" (BR) which is defined as u' = 0.7127 and v' = 0.4931 or (u'_{br}, v'_{br}). This offset is white-point (illuminant) dependent. Given a particular light source (u'_0, v'_0),

$$\theta = \tan^{-1}\left(\frac{v'_{br} - v'_0}{u'_{br} - u'_0}\right)$$

The forward mapping (HVC to XYZ) is equally straightforward:

$$L^* = Value$$

$$C^*_{uv} = \frac{13 \times Chroma}{C_f}$$

$$u^* = C^*_{uv} \cos(Hue + \theta)$$

$$v^* = C^*_{uv} \sin(Hue + \theta)$$

Finally, XYZ can be found from these as detailed earlier.

The TekColor† system (as distinct from the TekHVC† Colour Space, which it is based on TekColor)

† *TekColor* and *TekHVC* are trademarks of Tektronix Inc.

also defines various user-interface characteristics. In particular, there is a need to calculate the most "vivid" colour for a particular hue, which it calls the *MaxChroma* point. (One such case is when presenting the available hues for selection.) A detailed method for accomplishing this is given in [Tekta].

DIN System

The DIN System was originally developed in the 1930s and 1940s by the German Standardisation Institute (Deutsches Institut für Normung, DIN). It is defined numerically for illuminant D65, 2° observer surface colours in [DIN80b] and [DIN80a], although it is no longer available in any physical form. (Data are also available for illuminant C, 2° observer in a supplement to [DIN80b].) Its three attributes, hue number (T), saturation degree (S) and darkness degree (D), are usually written as *T:S:D*. These range from 1-24 for T, 0-15 for S and 0-10 for D. The standard defines:

$$D = 10 - 6.1723 \log_{10}\left(40.7 \frac{A}{A_0} + 1\right) \tag{6.31l}$$

where A = Y and A_0 is also defined in the standard. The exact value of 6.1723 is computed as $10/\log_{10}(41.7)$. This can be rearranged to give

$$Y = \frac{A_0}{40.7}\left(10^k - 1\right), \; where \; k = \frac{10 - D}{6.1723} \tag{6.31m}$$

The forward mapping (T:S:D to XYZ) uses the data points given in [DIN80b] together with an interpolation method described in [Witt79a]. (Note that the CIE standard illuminant D65 was used here — i.e. the data points were *not* transformed using the FST to match *real* conditions. Such a transform was unnecessary: the mappings were not used to display colours on the screen since no physical standard was available at the time of this work for visual comparison.) The algorithm begins by testing for neutral colours (S = 0), in which case the chromaticity is set to that of the illuminant (x_0 = 0.3127, y_0 = 0.3290). The DIN system is based on psychological scaling experiments which aimed to divide certain colour series into perceptually uniform steps. One of these colour series was for S=6, D=1. This can be used for colorimetric computation pertaining to other hue and saturation values. By taking (x, y, A_0) data from table 1 of [DIN80b] for each of the S=6 steps of T, twenty-four XYZ values (f[1] - f[24]) were calculated using Y values computed with equation (6.31m). (These data describe the locus for S=6, T=1 at each integral T step.) Then, for a given target T:S:D point:

$$I_T = \lfloor T \rfloor,$$

$$R_T = T - I_T.$$

are found and Lagrange interpolation [Atki89a] is applied to points f[$I_T - 1$], f[I_T], f[$I_T + 1$] and f[$I_T + 2$] to approximate the value of X_6, Y_6, Z_6 for the point T:6:1.

Determining XYZ for the target point, T:S:D, makes use of the property that the DIN saturation degree (S) is linear for CIE 1976 u'v' chromaticity coordinates. First, however, the $X_6 Y_6 Z_6$ must be transformed to u'v' coordinates. The normalised $X'_6 Y'_6 Z'_6$ centred around the illuminant as calculated:

$$X'_6 = X_6 \,/\, X_0, \qquad Y'_6 = Y_6 \,/\, Y_0, \qquad Z'_6 = Z_6 \,/\, Z_0$$

where $X_0 Y_0 Z_0$ define the illuminant used (i.e. D65, normalised such that Y=100). Then, the chromaticity coordinates (x', y') given by

$$x'_6 = X'_6 \,/\, (X'_6 + Y'_6 + Z'_6)$$

$$y'_6 = Y'_6 \,/\, (X'_6 + Y'_6 + Z'_6)$$

are used to compute (u'_6, v'_6):

$$u'_6 = 4x'_6 \,/\, (-2x'_6 + 12y'_6 + 3)$$

$$v'_6 = 9y'_6 \,/\, (-2x'_6 + 12y'_6 + 3)$$

Using the definition of S, the (u', v') coordinates of the target are found:

$$u' = (u'_6 - u'_0)S/6 + u'_0$$

$$v' = (v'_6 - v'_0)S/6 + v'_0$$

where u'_0, v'_0 are the chromaticity coordinates of the illuminant. These points then undergo the reverse of the earlier transformation:

$$x' = 9u' \,/\, (6u' - 16v' + 12)$$

$$y' = 4v' / (6u' - 16v' + 12)$$

Then,

$$X = X_0(x' / 100y')$$

$$Y = Y_0 = 100$$

$$Z = Z_0(1 - x' - y') / (100y')$$

From these XYZ, the target chromaticity can be established:

$$y = Y / (X + Y + Z) = 1 / (X + 1 + Z)$$

$$x = X / (X + Y + Z) = Xy$$

Using equation (6.31m), Y can be computed for this (x, y). The value of A_0 in this case is determined for T:S by linear interpolation (again using the data of table 1 of [DIN80b]) of the four neighbouring values of T and S. A detailed example of this entire process is given in Appendix G.

A reverse mapping (i.e. XYZ to T:S:D) was derived and this begins by computing h_{xy}, the hue angle of the target (x, y) as follows:

$$h_{xy} = \tan^{-1}\left(\frac{y - y_0}{x - x_0}\right)$$

where (x_0, y_0) define the chromaticity of the illuminant. This value is then used to locate T and r_1 by linear interpolation of the data points given in table 2 of [DIN80b]. Next, the (x', y') are found and used to compute (u', v'):

$$x' = 1.0522x / (0.1337x + 0.0816y + 0.9183)$$

$$y' = y / (0.1337x + 0.0816y + 0.9183)$$

$$u' = 4x' / (-2x' + 12y' + 3)$$

$$v' = 9y' / (-2x' + 12y' + 3)$$

This enables r to be determined:

$$r = \sqrt{(u' - u'_0)^2 + (v' - v'_0)^2}$$

Then, by definition, $S = r / r_1$. The darkness degree, D, is then found using equation (6.311) with the value of A_0 determined for T and S as before.

6.3.2 Performance Evaluation

Once derived, the performance of the mappings had to be assessed. For RGB, CMY, HLS, CIELAB, CIELUV and TekHVC this was simply a matter of verifying that the software written correctly followed the various formulae defined elsewhere. For the other systems, two types of verification are possible:

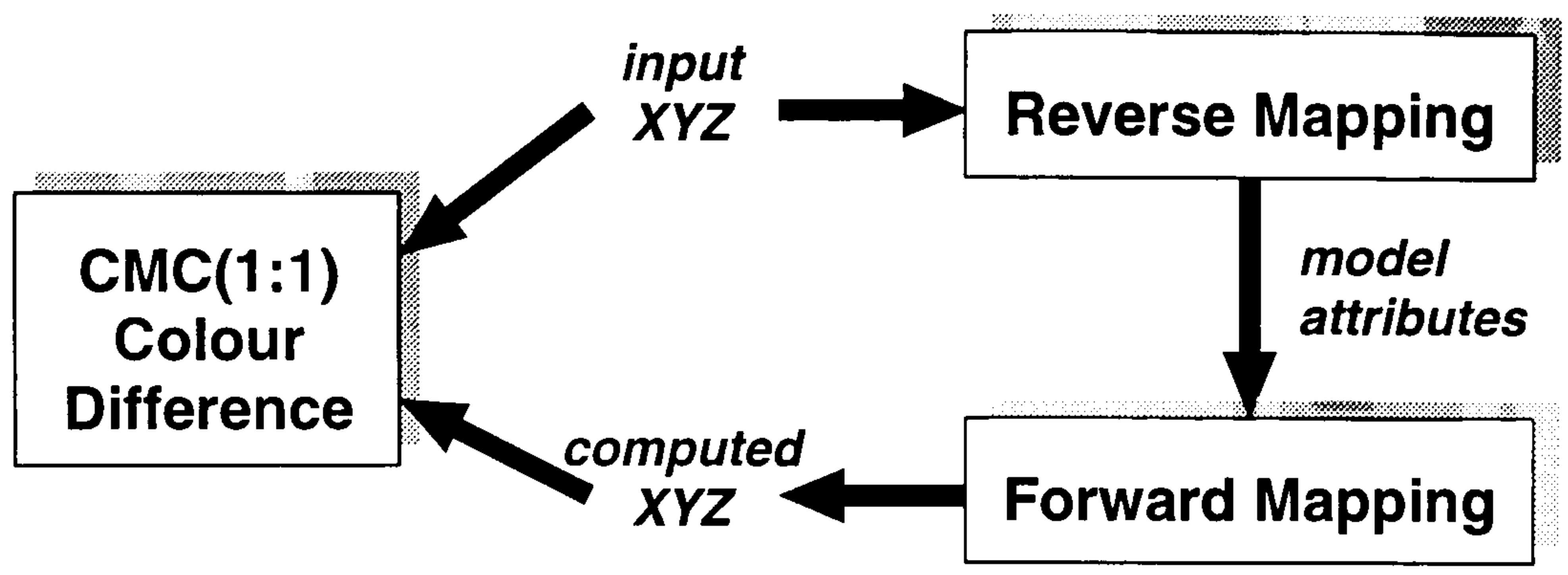
- **Subjective**

  The simplest but most severe test is a visual comparison of the colours described within the colour space of a particular system. Any visual non-uniformities or other anomalies are readily apparent (although this might be a "feature" of some systems). A comparison can be made with physical samples, where they exist (e.g. the Munsell Book of Colour). This can be done by placing the colour atlas inside a viewing cabinet (whose light source is measured and used as part of the various colour calculations given earlier) and comparing the appearance of this with that of the screen colours. This method has the disadvantage of requiring that appropriate display software be written for each system.

- **Objective**

  If available, some specific *known* examples can be used. It is also possible to use just the "aim points" (i.e. the colours making up the database used for interpolation), however this does not check that the interpolation method is working properly. Another approach is to combine the forward and reverse mappings to see whether the computed colour is sufficiently close to that input (see Figure 6.3). This method has the advantage of testing both mappings at once, but does *not* guarantee that the intermediate (colour notation system) attributes correspond well to those of the particular system.

Figure 6.3: Using Forward and Reverse Mappings to Test Performance



In [Smit90a] several steps were taken to ensure the consistency of both the database and program used for colour conversion. For the database, these steps included cross-checking using redundant information (if, for example, both XYZ and CIELAB notations are available), checking the ordering and range of the data and visual examination (of the numbers). They verified the transformation software by mapping some 47 systematically chosen Munsell atlas sample points to the various other colour systems (via XYZ) and then back again to Munsell coordinates. These were then compared with the original Munsell coordinates. Note that this only checks the reversibility and not the accuracy of the model. Visualisation software was not part of this system, thus precluding a visual examination of the colours on screen.

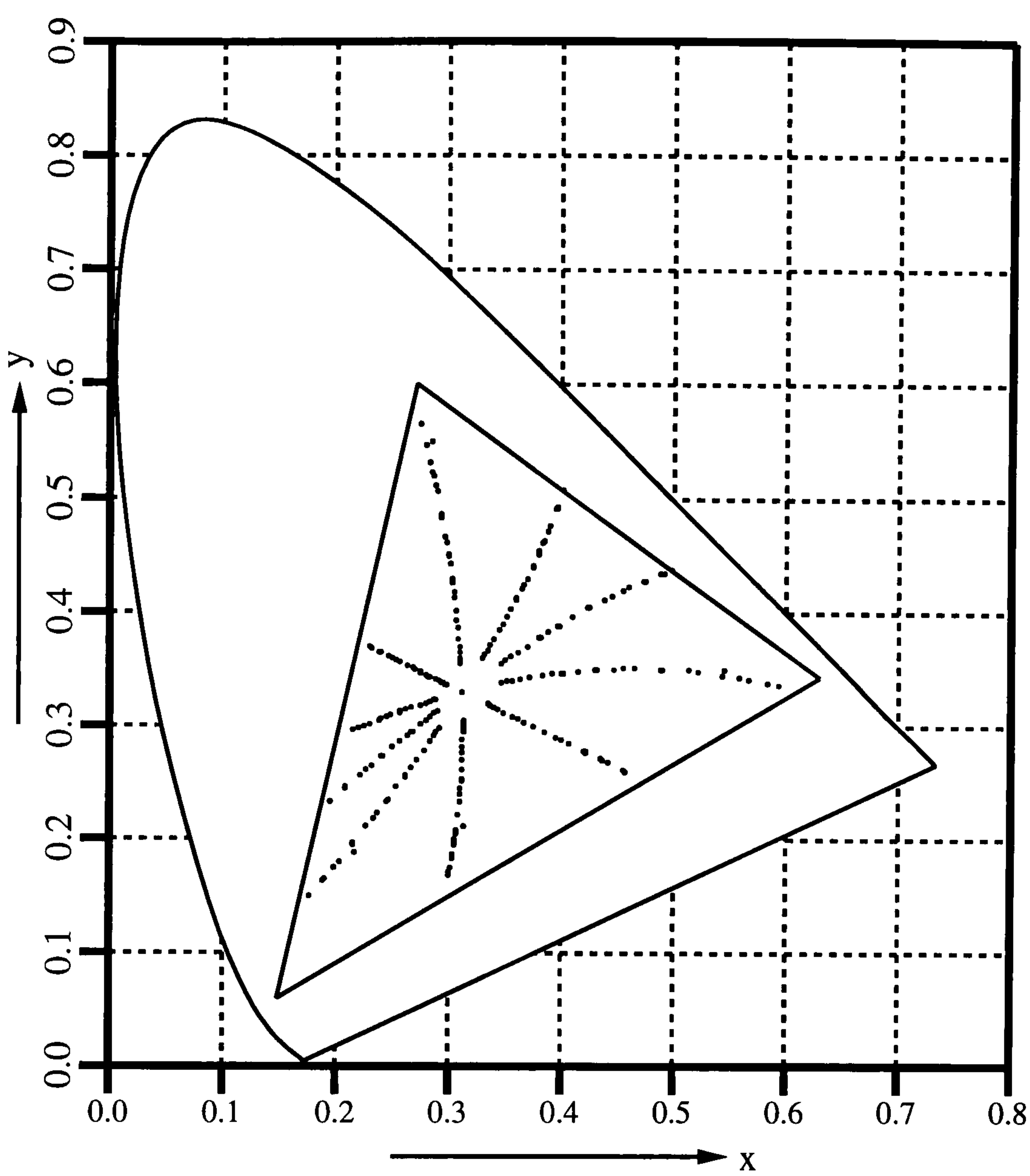
For the work described here, no additional effort was spent to verify the various databases used — repeating the work of Smith *et al* was felt to be out of the scope of this work. (However, much of the data used were obtained from "official" sources and where this had to be manually entered, these were checked for mistakes.) It must be noted that, as mentioned in [Smit90a], the mapping software:

"...can only be as accurate as the data and equations used in the the conversions."

Verification instead concentrated on two areas. The first method (objective) was to combine the reverse and forward mappings, as described earlier. A dataset of 267 points, chosen from CIELAB space to cover a wide area of display gamut, was used. These are plotted in Figure 6.4. (These data were the same as were used in [Luo91a], called the "uniform test set.")

For NCS, a total of 44 points (16.5%) yielded a CMC ΔE greater than 0.001 units. Of these, 34 (13.5% of the total) were outside of the boundary defined by $s + c \geq 98$. One further point (0.4% of total)

Figure 6.4: Data Points Used to Test Reversibility of Mappings



was white (i.e. s = 0). For Munsell, a similar figure of 53 points (19.9%) had a ΔE value exceeding 0.001 units. Again, most of these were due to boundary conditions (high or low Value or Chroma) or due to the target samples falling outside of the notation system's aim point database range. Using OSA, all points except one (for which the OSA to XYZ mapping failed) gave ΔE values generally much less than 0.001. Finally, the DIN results were as follows: 3 points (1.1%) had $0.3 \geq \Delta E > 0.2$, 16 points (6.0%) had $0.2 \geq \Delta E > 0.1$ and the remainder (92.9%) of the points had $\Delta E \leq 0.1$. The mean ΔE for the DIN test was around 0.045 units. Testing the Pantone mappings using this method was not really practical due to the nature of that system. (That is, having only a small number of samples and not being able to use interpolation means that large colour differences from the target point are inevitable.)

A typical ΔE value used for colour quality control in the textile trade is one unit (with two samples placed side by side and presented on identical substrates). All the ΔE values are well within this figure which would indicate that the accuracy of the model mappings is highly satisfactory. The results of this objective test were quite favourable; the majority of the larger errors were due to the target point being out of the range for that particular system's aim point database. For colour model visualisation this is not a problem, but for interconversion of colour order system data this could prove troublesome — though there is not a lot that can be done† to remedy this situation.

The second (subjective) test was done at a later stage once appropriate colour model visualisation software had been developed. For those systems existing in atlas form, a visual comparison was made between screen and physical colours. In the case of Pantone, this was the *only* verification necessary as the database had been obtained from the manufacturer. For all sample-based systems, performance was judged qualitatively by several experienced colour observers and the match between screen and atlas colours was found to be highly satisfactory. Note that because the data used had undergone a transformation using the FST, fidelity could not simply be assessed by comparing the measured results of screen and physical samples — the match is intended to be on the basis of appearance rather than colorimetric values.

6.4 DESIGN OF THE PROTOTYPE

After some initial interviews had been held with textile designers (see Chapter 3), their basic requirements for a computer-based colour selection system were established and a basic understanding of their existing methods was known. This system, *ColourTalk* [Rhod92a, Luo92b], was to be centred around the creation, visualisation and management of colour palettes and *not* a complete design system.‡ At that time, the exact form that any solution to the designers' colour fidelity problems should take could not be predicted with sufficient confidence. It was therefore decided to first construct a prototype system which could subsequently be shown to designers and modified or extended as proved necessary (i.e. it would be user-driven).

† Extrapolation of the aim point database, for example, could locate colours out of this range but their attributes would be meaningless for the particular colour notation.

‡ There are already many CAD systems in existence and implementing yet another would not have been worthwhile.

Another problem was that a few of the designers had little experience with modern graphical user interfaces. To circumvent this, a series of paper mockups of the proposed screen layout were first shown to them.

The hardware used for the prototype (and later the *final*) system was based around a Sun workstation. This included a 24-bit framebuffer (capable of reproducing over 2^{24} or 16 million different colours) which drove a Barco Calibrator monitor. A Verivide viewing booth with simulators for illuminants† D65 (average daylight), TL84 (widely used in the textile trade), WF (white fluorescent — office lighting) and A (tungsten — room lighting) was used for surface-screen matching, although the D65 simulator was used for the majority of tasks. A separate Coats Colour Physics System (CPS) was included for recipe formulation tasks. The software was, for portability across other UNIX-based platforms, written in the C programming language and made use of the X11 windowing system.

6.4.1 Components of the Prototype System

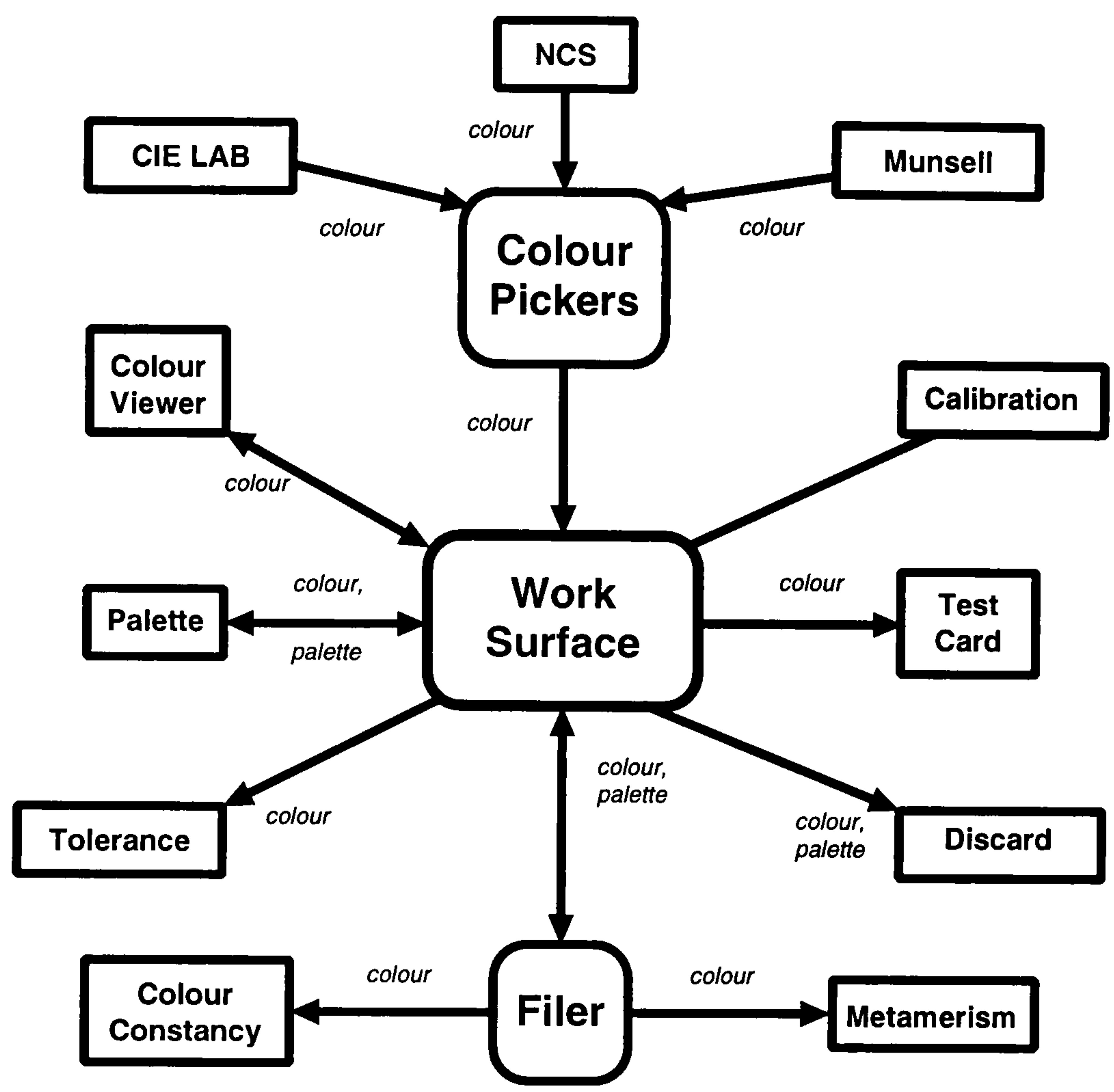
The basic components for such a system were outlined in §5.3.4. As a result of wanting to further add to and modify the system, it was designed to be modular (rather than monolithic) and to be readily extensible (e.g. with other domain-dependent applications). Each function was logically independent but able to communicate colour information to the other parts of the system. All such communication is via a special window called the *work surface*. This is a large window with fixed icons representing the available functions. Individual *colours* and groups of colours — *palettes* — are also shown in this area as object icons. These object icons can be moved around the screen and "transmitted" to other applications by "dropping" the object icon over the appropriate function icon.

The functions available in the prototype system are: colour selection, palette creation and storage together with various tools for visualising various colour phenomena. These are illustrated in Figure 6.5 which also shows how colour and palette information may be transferred between each of the various tools. Each application window was presented on a neutral background (to minimise colour contrast effects)

† Note that the *real* light sources were actually measured in order to attain a good match. For example, the chromaticity of the D65 simulator used was (0.3320, 0.3401) versus the *standard CIE* illuminant (0.3127, 0.3290) which *is* significantly different.

corresponding to that used in the viewing booth.

Figure 6.5: Overview of the Prototype System



6.4.2 Colour Selection

Colour information can be entered into the system using a variety of methods. It is frequently the case that the textile designer's starting point is either from *existing* colour palettes or from other *external* sources (e.g. fabric swatches, pieces of yarn or photographs). Getting these colours into conventional CAD systems requires extensive colour matching effort, and often the screen appearance is completely overlooked in favour of getting the final printed output to look right. Using the ColourTalk system, designers are able to measure colours via the spectrophotometer attached to the CPS. These data can then be transferred via local area network or floppy disk to the main system (see §6.4.4). Alternatively, colours may be selected using the system's colour model visualisation tools.

Three colour notation systems were provided in the prototype system: CIELAB, Munsell and NCS. At the time the prototype system was being developed, the colour mapping software was incomplete. To get around this, fixed lookup tables containing pre-computed aim points were used. Each colour system was presented in its own window which was divided up into three main areas. The first area shows a cross-section though the colour space of constant lightness, Value or blackness according to the colour system (see Colour Plate 1). This area serves for hue or colourfulness (Chroma or chromaticness) selection. Another view presents a perpendicular cross-section of constant hue. Colours can be chosen by selecting the desired screen colour patch from either view. Selecting a patch from the constant "lightness" view causes all those colours in the constant hue view to take on the same hue as was chosen. Similarly, the "lightness" of the constant hue view can be adjusted by selecting a patch of the desired "lightness" from the constant hue area. In both cases, the selected hue is indicated by a small black border around the patch.

These two views provided for *coarse selection* only, due to there only being a small number of colours available. Once the region of colour space encompassing the desired colour has been located, a third smaller viewing area is available for *fine selection*. This presents a CIELAB *micro space* view of the colour (the other two were *macro space* views). In this area, any *one* of the three CIELAB attributes (L^*, C^*_{ab} or h_{ab}) may be fixed, allowing small adjustments to be made to the other two. The target colour is shown in the centre of a grid of twenty-four surrounding colours, each differing from its neighbour by a fixed amount of L^*, C^*_{ab} or h_{ab}. When an adjacent colour patch is selected, this then becomes the new target shade and the whole micro-space view shifts accordingly to re-centre on this colour. The degree of difference between the neighbouring patches may be controlled individually for each attribute by adjusting a "scrollbar" on the screen. Progressively finer changes may be made until the desired colour is located.

The approximate position of the target colour, as it is adjusted in the micro space, is also shown in the two macro space views. Once the user is satisfied with a colour, it may be transferred to the work surface for subsequent use in other parts of the system.

6.4.3 Palette Creation

From discussions held with the designers, it was found that the exact format of a colour palette is critical to its perception — in particular, the size and organisation of the colour patches can affect the mood of the palette. Although there is no standard palette layout used by industry, various decisions can be made to control this format. (A fixed format is essential for palette communication: if the colours are presented differently, they will be interpreted differently.) A regular grid of 6 × 4 patches was chosen as being typical, with each patch being of size 3cm × 2cm (or similar in aspect ratio). This corresponds closely to the typical size used for physical palettes. According to the designers, smaller sizes would not be acceptable as the colour would "lose its strength." The rectangular shape of the patches was aimed at "drawing the eye to the edges of the colour." The grid arrangement enables the designer to group colours into columns or rows if required. Also, the spacing between these patches was chosen so as not to visually emphasise either the columns or the rows.

Some other requirements of the designers were identified in Chapter 3. These included seeing the colours against different backgrounds, saving completed work and the ability to adjust shades collectively or independently. The ColourTalk prototype's *palette* tool (which is shown in Colour Plate 2) sought to satisfy all of these goals. Within the fixed format, colours could be moved around and exchanged under mouse control between the palette area cells. (Colours can also be moved to and from the work surface area as before.) The palette background could be set to black, white or grey (the default). Directly below the 6 × 4 grid of colour patches, a second area — the *work area* — was available for colour adjustment. Into this area, colours from the main palette area could be copied. Because the designers had asked for the ability to see colour under several stages of transition, the work area included two rows of six colours. The top row was used to hold each starting colour (up to six at a time) and the second row showed the results of colour adjustment.

Colour adjustment was performed on an LCH (CIELAB) basis using three on-screen slider controls. Thus, single or groups of colours could be adjusted at once, allowing the designer to, for example, darken several colours by the same amount. While adjustment is being made, a simple chart (which is also depicted in Colour Plate 2) provides feedback as to each colour's relative position within CIELAB space.

If, after colour adjustment, the new colours are acceptable, they may be moved back into the main palette area — possibly replacing their original counterparts if so desired.

6.4.4 Palette Storage and Communication

The prototype system supports the storage and retrieval of colour palettes via its *filer* function. The external representation used for colour information was that described in §5.3.2. The storage media available was either the system's hard disk or a 3½" floppy disk. Colour data could be communicated via floppy disk to the CPS (later a network link was established). This enabled a newly created palette to be loaded into the CPS, have a dye recipe formulated for each of its colours and then be loaded back into the prototype system. This also provides another means of entering a colour: existing swatches can be measured via the spectrophotometer attached to the CPS and then the spectral data transferred to ColourTalk for inclusion in colour palettes, etc.

For measured colours, or for those which are used for recipe formulation (in the CPS), there is an associated spectral reflectance curve included in the information held for each colour. This may be used for various visualisation tasks described in the next section. When generating recipe formulae, the CPS uses only the CIE XYZ data to identify a colour. This usually means that there are several possible recipes (each having different reflectance curves but leading to the same XYZ) which can be used to match under illuminant D65. However, these recipes might not match under other lighting conditions. Another approach to this problem of *colour constancy* is to generate *pseudo-reflectance curves* [Hawk91a] for each target shade. This information is "illuminant independent," meaning that the CPS can use this to select only those recipes which match under *several* light sources. However, there is no guarantee that pseudo-reflectance curves will actually produce colour constant shades nor that shades can actually be produced to fit these curves (e.g. due to the limitations of the actual dyes used).

6.4.5 Colour Visualisation

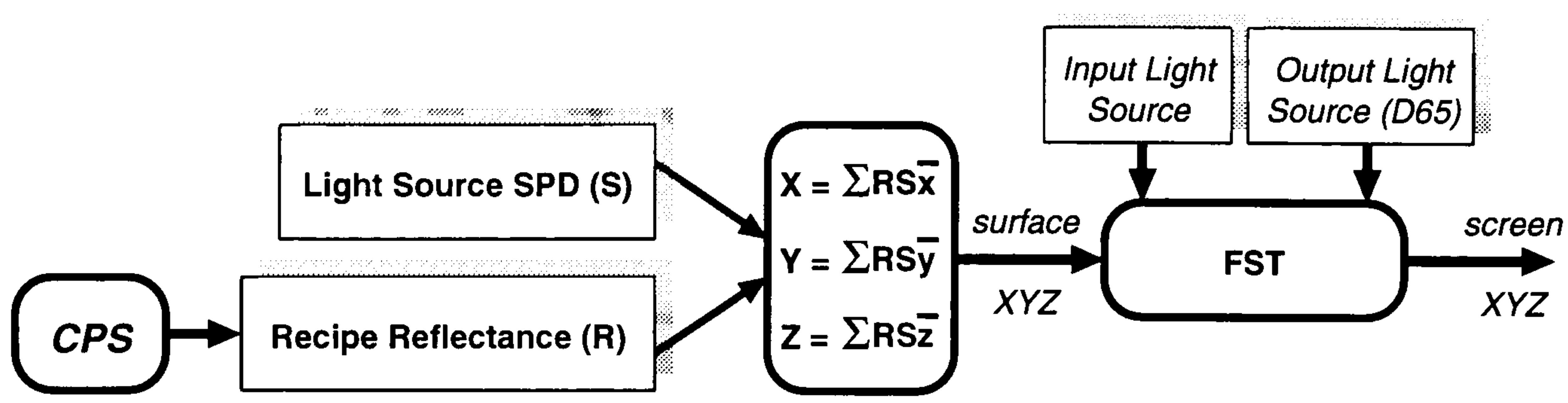
Another of the designers' requirements was to examine colour combinations. Individual colours can appear very different to when they are seen next to, or surrounded by, other colours. Furthermore, colour is seldom used in isolation by most designs and so it is vital to be able to see how various colour combinations will appear before the palette is finalised. (This phenomenon of *colour contrast* was introduced earlier in §2.2.3.) Colour appearance is also affected by size and background [Beck72a, Jame61a, Tipl82a, Scri91a], however the exact magnitude of this effect is difficult to predict quantitatively. Therefore, ColourTalk provides a means of visualising and experimenting with colour contrast by enabling simple rectangular colour patches (taken from any colour palette) to be overlapped and resized (as shown in Colour Plate 3). To compensate for any undesirable colour shift (or possibly to *enhance* contrast to create special effects), the prototype system also permits further LCH adjustment of individual colours in a manner similar to the colour adjustment function described earlier.

Although the representation used by the ColourTalk system does guarantee colour constancy, software was written to provide visual feedback as to which of the CPS-generated recipes satisfy this property† (depicted in Colour Plate 4). The system is able to simulate, for each of the colour's recipes, the colour appearance under any of the light sources found in the viewing booth. Furthermore, one, two or four light sources can simultaneously be shown on the screen at once. A reference white is also displayed in each view to assist in colour judgement. This makes it easy to identify which of the recipes suggested by the CPS are likely to appear the most similar under a variety of viewing conditions. The simulation uses the FST described earlier to process the XYZ (which is computed from the spectral reflectance data, R%, of the recipe together with the spectral power distribution (SPD) of the light source). The components of this process are illustrated in Figure 6.6. A similar function permits metamerism to be assessed for pairs of colours. (This might be useful where a garment was to be made up of two different materials, each necessarily requiring a different dye recipe. In such cases, the two pieces of fabric may fail to match under certain lighting conditions.)

The final stage of colour palette design is to have fabric swatches dyed in the chosen colour palette shades. This work is carried out by a dye house which is often external to the design business itself. During production, batch variations are unavoidable and it is important to have an advance agreement as to

† As part of the recipe formulation process, the CPS is able to predict the final reflectance curve with reasonable accuracy based on the spectral data held as part of its dyestuff database.

Figure 6.6: Simulating Colour Appearance for Different Light Sources



exactly what level of variation is to be acceptable. As part of the ColourTalk prototype, the user is able to specify exactly what degree of "colour precision" is required for each individual colour and instantly view the consequences of this on the computer display via the *colour tolerance* function (see Colour Plate 5). Colour tolerance is specified using the CMC(2:1) colour difference formula in terms of either an overall measure (ΔE) or individual lightness, chroma and hue (ΔL, ΔC and ΔH) values. The latter representation might be used where, for example, the hue of a colour must be more accurately matched than either its lightness or chroma.

Within this function, the effects of a particular colour tolerance setting are visualised as three cross-sections through a colour difference cube. Each view depicts the target shade surrounded by other coloured squares. Directly adjacent neighbours have negative or positive ΔL, ΔC or ΔH differences from the target. (Out of gamut colours are not shown since an *approximation* to such a colour displayed on the screen would not be helpful in assessing colour difference.) Diagonally adjacent squares show the combined effect of two of these differences. Moving either the ΔE or one of the ΔL, ΔC or ΔH scrollbars assigns a new tolerance setting and changes the three views accordingly. Although helpful, these three views are insufficient for making realistic colour tolerance decisions. The problem of batch colour variation in the production process is most vividly demonstrated when the completed garments are "racked" together on display at the point of sale. With such an arrangement, an incorrect colour stands out immediately. ColourTalk is able to repeat this exercise by simulating a typical batch of fifty colour samples chosen at random to lie within the current colour tolerance setting. From these fifty samples, pairs of colours may be selected to investigate their mutual colour difference (ΔE, ΔL, ΔC and ΔH figures are reported on the screen). It is quite possible that the *combined* difference between these may exceed the specified tolerance setting if they deviate in opposite directions from the target shade.

6.4.6 Display Calibration

The procedure for calibrating the system's Barco monitor, detailed in §6.2.1, was incorporated into the ColourTalk system and this function is activated by selecting the calibration icon from the work surface. As a further safeguard, a *Macbeth Color Checker Chart*† is used: this is reproduced on the screen and is visually compared to a real chart positioned in the viewing booth (under D65 lighting). This enables any calibration problems to be identified very quickly before the system is used.

6.5 THE FINAL SYSTEM

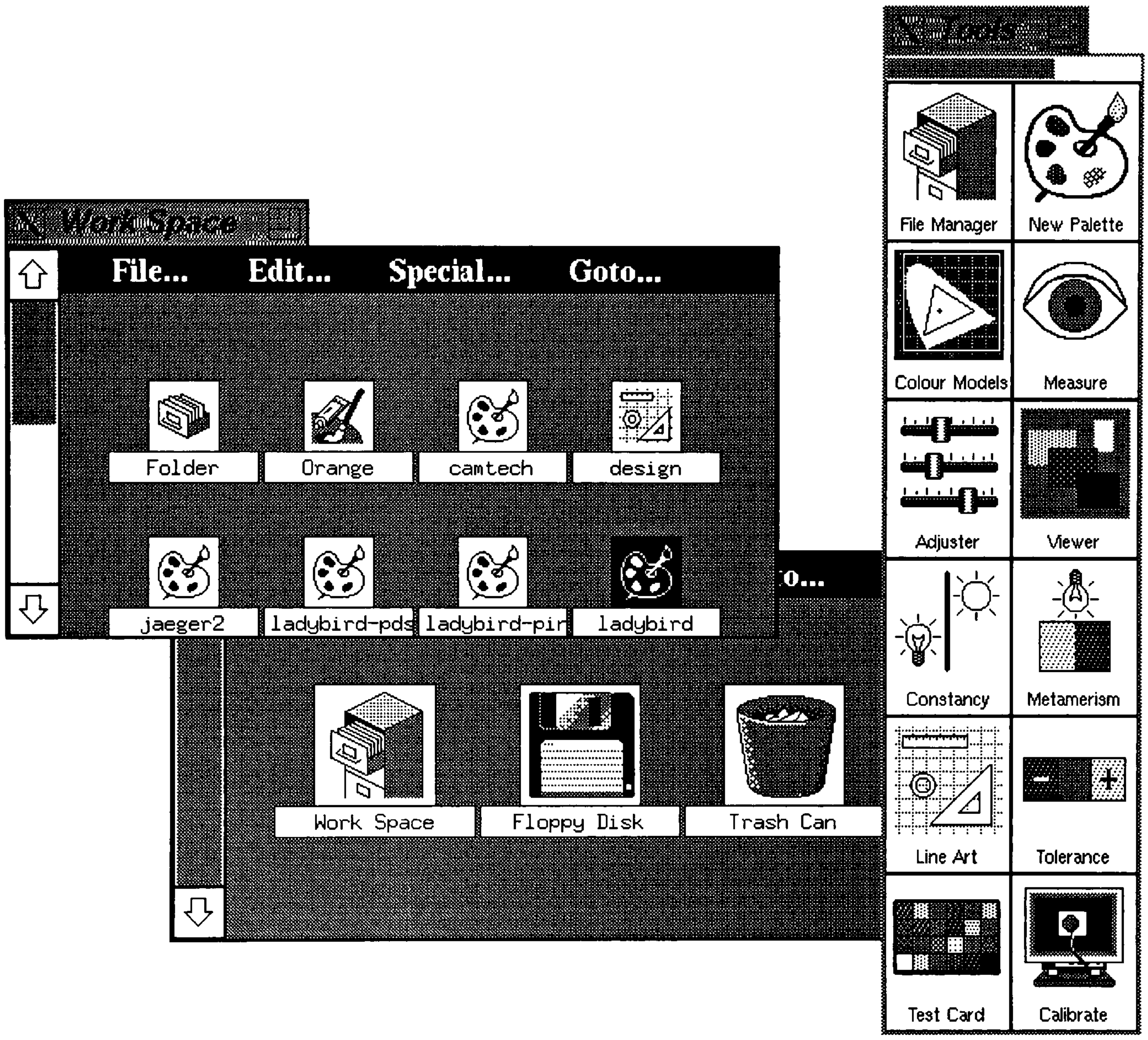
The prototype system was developed with a view to subsequent modifications and additions being made. Also, its very short (three months) development period dictated that certain compromises had to be made in order to meet this deadline. The final system, completed over a much longer period, filled in these gaps, improved the system's usefulness and efficiency and added new functionality.

The major user interface change from the prototype was to eliminate the work surface. Communicating colours between applications via this intermediate step (i.e. application A to work surface to application B) was not very efficient and was not consistent with other software written for this windowing environment. (Another problem was that the work surface was *large* and tended to slow down screen updates.) Instead, the work surface was replaced by a much smaller *tool menu* window containing just the iconic representations for each of the system functions, shown in Figure 6.7. The colour exchange aspect of the old work surface was implemented using the "standard" X Windows select mechanism [Nye90b]. Colours could then be "cut" or "copied" from one window and subsequently "pasted" into another. The "cut-paste" data that is transferred via the X selection process is textual and in the same format described earlier (specifically, it contains XYZ information which is used to describe the screen colour). This enables

† This chart is frequently used in the photographic industry to assess colour reproduction.

colours or palettes to be "pasted" into non-ColourTalk applications, such as text editors or electronic mail systems (thereby enabling the direct remote communication of precise colour information to other users).

Figure 6.7: The ColourTalk Tool Menu and Filer



The final system provides *nine* colour models for interactive colour selection: RGB, CMY, HLS, Pantone, CIELAB, CIELUV, Munsell, NCS and TekHVC (shown in Colour Plates 6-8). Where appropriate, the user interface for each was designed to resemble the physical standard (to help users who are already familiar with the system). No attempt was made to improve the usability of either the RGB or CMY systems: although their counter-intuitive attributes make them difficult to work with, any other arrangement using perceptual attributes would define completely different models (which is essentially what the HLS model is doing). Since each of these colour model tools also support the "cut and paste" paradigm, it is possible to copy, say, a particular colour located somewhere in Munsell space and paste it into NCS. (The same colour will then be located in NCS space and displayed using NCS notation.) This means the user is able to *visually* interrelate between the various colour systems by transparently using the bidirectional mappings described in §6.3, thus enabling rapid colour conversion between different notation systems. In the case of the Pantone system (which has a limited number of samples), when a colour is pasted in, the CMC(1:1) ΔE colour difference between the target and located colours is displayed in addition to the "closest" match. This is in order that the user might appreciate how far off the "closest" Pantone shade actually is.

Other new functionality included the facility for *direct* colour measurement. A Macbeth MS-2020 spectrophotometer was connected to the system and software written to support this. The colour measurement tool then displays the measured colour which may be cut or copied for use in other parts of the system. (This expedites the creation of colour palettes based partly or wholly on existing physical samples.) The file management function was completely rewritten to take advantage of the new cut and paste operations. Whereas before it had presented a mainly textual list of file names, the new version portrays each object type as a different icon (see Figure 6.7) which makes finding objects a much more efficient process. The cut/copy/paste idea, when applied to colour data files, enables them to be deleted, duplicated and moved around within the computer's file system in addition to being able to communicate these objects to other applications.

Although it was not an aim of this work to build a complete CAD system, it was felt that providing very limited design facilities would demonstrate the system's applicability to a typical CAD environment. For this purpose, an existing structured drawing program was acquired and modified to permit ColourTalk palettes to be loaded in (see Colour Plate 9). By scanning simple black and white line art, this can then be colour-filled using palette colours. By re-ordering colours within a palette, the same design can be seen in several different colourways.

Another "real" application developed was to display colours from a shade database. As a sample, the Coats International thread range was used. This application behaved much like the Pantone tool mentioned previously: colour could be selected from its "pages" or the closest shade could be located for any given target colour. The designers or thread manufacturers would typically use this to choose a thread (or locate the closest existing thread) to match colours used in a design in order to save the time that would otherwise be spent manually finding such a thread.

Various changes were made to the other parts of the system as a result of the experience gained in having used the prototype for some time. The colour adjustment component of the system's palette window was made into a separate function. This has two main benefits: firstly, the palette area is reduced in size and complexity and secondly, it means that adjustment is possible from *other* applications via cut and paste. Other less visible changes were the ability to resize many of the windows so that, rather than having just one or two *large* windows visible on the screen at once, better use could be made of valuable display "real estate." (Smaller windows are also much less demanding of system resources and are therefore much faster to manipulate.) A single level "undo" function was added to certain "critical" functions (e.g. pasting one colour over another). Finally, the colour tolerance program was also modified to include the CMC(1:1) colour difference measure in addition to CMC(2:1). The CMC(2:1) value is normally used by textile workers, however there is some evidence to suggest that when applied to solid screen colours (which have no texture, unlike their fabric counterparts) the lightness difference appears much greater than for textiles. Hence, both the CMC(1:1) and CMC(2:1) formulae are offered.

Although the ColourTalk system used a 24-bit display, such hardware is typically much more *expensive* and *slower* than the more commonplace 8-bit graphics hardware.† The system was therefore adapted to operate in such an environment in order to greatly expand the number of systems on which it could be run. An 8-bit X terminal was calibrated for this purpose and this was found to perform adequately.

Work done elsewhere in the CARISMA Project included the characterisation of various printing devices [Luo92a]. This included a Mitsubishi G650 thermal wax device which was directly linked to the system. Functions were added to exploit this, permitting colour palettes and line artwork to be printed. In keeping with the philosophy of ColourTalk, hardcopy is also a WYSIWYG process (i.e. there is no gamut compression applied). This facility would be useful to designers wishing to proof their designs (or

† An 8-bit display is capable of displaying 256 colours simultaneously, each colour being taken from a palette of over 16 million (2^{24}) colours — hence the colour resolution is actually the same. The only difference between the 8-bit and 24-bit displays used was the number of colours displayable concurrently.

communicate physical palettes) whilst still maintaining a high degree of colour fidelity.

6.6 EVALUATION

The system was evaluated in a number of ways. Absolute colour fidelity of the display was given in §6.2. For a true WYSIWYG system like ColourTalk that employs a colour appearance model (itself assessed in [Luo91c]), a direct colorimetric comparison of screen and physical colours is not altogether meaningful. A visual assessment by a panel of experienced colour observers would seem to indicate that the appearance match is highly satisfactory. A limited verification of colour model interrelation was given in §6.3.2.

As part of its evaluation, ColourTalk was used for a real design task. A designer from the Coats Viyella Design Group created a colour fashion palette for a well known childrenswear company. Colours were created using a mixture of colour matching to existing fabric and paper samples and also using the system's colour "pickers." Recipes for this palette were then generated using the Coats CPS and ultimately fabric swatches were dyed. Some earlier work was also done to dye samples chosen from the screen. Reflectance data was sent to the dyers who produced samples in cotton material. For the twenty-two colours tested, the average CMC(2:1) colour difference was around one unit for the D65 simulator. This is well within the acceptable range used by industry. Finally, the ColourTalk system, together with examples of its output were used as part of the final exemplar for the CARISMA project.

6.7 SUMMARY

In this chapter, an implementation of the ideas of the previous chapter was given; this forms ColourTalk — a system which *has* demonstrated the practicality of WYSIWYG colour fidelity and communication within a textile design context. The system focuses around the creation of fashion colour palettes but also includes a number of "colour management" functions which should be applicable to other computer supported work where colour fidelity is a concern. In addition, a number of popular colour systems are provided for colour selection and these have been mathematically interrelated, thus enabling communication of colour information between users of disparate colour notation systems. The system has undergone limited evaluation for a real design task and, in terms of the original requirements put forward by the designers and its colour fidelity performance, it can be seen to have met its design goals. The system, as it stands, has two main limitations. Firstly, its WYSIWYG performance is currently all or nothing: out of gamut colours are not considered. Secondly, the system does not provide full CAD facilities. This last point can also be considered an advantage because not being tied to one particular system means that the various tools comprising ColourTalk can be readily applied to any existing application or domain.

Chapter Seven
Conclusion

CHAPTER SEVEN: CONCLUSION

7.1 SUMMARY

Colour is currently a problem for industry. Modern computer aided design systems, whilst being both flexible and powerful for a wide range of tasks, can also create more work for their users. In the preceding chapters, it has been demonstrated that both the *communication* and *fidelity* of colour across different media are of concern to those activities in which colour plays an important role. Whilst many of the colour management systems that are beginning to emerge onto the marketplace do attempt to tackle some of these issues, their performance is frequently unsatisfactory. There are several reasons for this. First and foremost, there is no consideration towards the *appearance* of colours (vital since colour perception is a highly complex process). Instead, colours are assumed to match on the basis of instrumental readings. In addition, some sort of gamut mapping between devices is frequently carried out in order to maximise the utilisation of the range of colours available on a given target device. While this often results in a pleasing look for photographic images, individual colours typically do not match each other. Many users of computer systems requiring a good (or absolute) colour correspondence are forced to resort to time-consuming manual matching procedures for each medium that is involved. One final key area of difficulty is in specifying colour. A number of very different notation systems are in everyday use and, as a consequence, this can hinder effective colour communication between "incompatible" representations.

The solution that has been proposed to these problems applies a number of existing techniques to achieve WYSIWYG communicable colour. Firstly, devices are characterised colorimetrically to yield device independent colour. Building on this, viewing condition independency is realised through the application of a colour appearance model. As there are already numerous colour notation systems in use, this approach aims to support many of these by implementing them mathematically. This then permits colours which are specified using one system to be precisely exchanged with those of another notation. The solution does *not* try to re-invent a complete CAD system; there are already numerous highly complex examples of these available and, in any case, it was found that the requirements for such a system are highly application-specific. Instead, it is envisaged that the same methodology proposed and proven here be incorporated into existing CAD and colour management systems.

The second chapter introduced colour science and technology. The everyday phenomenon of colour was shown to be the result of the interaction between the light source(s), the object being viewed and the observer. Changing the properties (such as geometry) of either usually results in a different perceived colour. Colour vision is essentially tristimulus in nature meaning that a colour can be uniquely represented by three values. Whilst the CIE system of colorimetry was seen to be sufficient for the purposes of numerically describing a colour stimulus, it says nothing about its *appearance*. Such limitations have been overcome by modelling the appearance of colour. Colour appearance models extend the scope of conventional colorimetry by predicting the effects that viewing conditions such as illumination, background and media have on human colour perception. Also introduced were various colour notation systems. A number of these are in use throughout industry and have proven quite successful. One limiting factor to their effectiveness, however, has been the difficulty encountered when trying to exchange colour information between different notations. The chapter concluded with a look at the technology used to reproduce colour, concentrating mainly on the CRT display and printing devices commonly in use.

Chapter three looked at the typical colour control processes involved in textile garment design. This study centred around a series of interviews conducted with several groups of designers. Their work was found to involve the use of seasonal colour palettes and although the majority used CAD systems to various extents in their work, they all suffered from the common problem of poor fidelity in the reproduction (across different media) and communication of colour. Although their detailed requirements for CAD were seen to be both non-uniform and task-specific, their need for improved colour fidelity is by no means uncommon. Hence, it was proposed that a solution to these problems, even though it might entail elements which are domain-specific, would still be applicable to other areas involving colour computer systems.

The fourth chapter investigated the current state of the art in tackling the problems of colour fidelity and communication. The concept of WYSIWYG colour was introduced together with various commercially available colour management systems that attempt to address colour fidelity. At present, none of these make use of colour appearance and most overcome gamut limitations by applying non-WYSIWYG gamut transforms. The chapter also looked at efforts to present colour spaces on computer displays and as to how different notation systems could be interrelated (in order to aid colour communication). To date, very little work has been done to present multiple colour order systems using a computer. As a consequence, most design systems fail to provide adequate colour selection and communication tools. Existing proprietary solutions which attempt to address the problems surrounding colour in design systems were investigated. Finally, some of the obstacles to achieving high colour fidelity on computer displays were discussed, in particular in the simulation of small colour differences. Ultimately, however, it was concluded that while such systems are perfectly feasible, they are ultimately constrained by the colour gamut and quantisation properties of the display hardware.

To address the limitations of existing approaches, chapter five outlined a proposed solution aimed at fashion CAD system users. In such an environment, WYSIWYG is essential as cross-media colour matching is a vital element of the fashion designer's work. WYSIWYG colour fidelity, as already stated, can be achieved through the application of colorimetry and colour appearance modeling which may be combined in a "four-stage transform." For each colour imaging device, this entails both device characterisation and calibration. To implement and interrelate different colour notation systems, it was proposed that each be defined in terms of a bidirectional mapping to CIE XYZ. A number of colour management tools were also suggested which were more specific to textile fashion design tasks.

Following directly on from this, the sixth chapter went into more detail concerning the tendered solution. As part of this, it looked at an actual computer-based system, ColourTalk, that has been implemented to demonstrate the practicality of the approach. Specific details were given concerning monitor calibration and characterisation, how the various colour notation systems were modelled mathematically and how these models were subsequently verified. The various functions of this system and the tools it provides were described. Finally, the system's evaluation was discussed both in terms of its colour accuracy and its effectiveness when used for a real design task.

7.2 APPLICATIONS

In this thesis, a method has been given for achieving both WYSIWYG colour fidelity across different computer-controlled imaging devices and also for achieving WYSIWYG colour communication between computer users. The solution that has been presented is oriented towards the textile fashion design industry because the requirements for colour fidelity and colour communication there are particularly demanding. Where fidelity is poor, there is a significant cost to industry as a result of the time and expense involved in re-matching shades. Imprecise colour gives rise to a lack of confidence experienced by the buyer, thus making a sale less likely. Conversely, having a high level of confidence in the ability to reproduce colour may ultimately mean that buyers are able to select designs on the basis of on-screen simulations which would have a significant saving in the cost of having physical mock-ups produced. The ability to communicate colour accurately is equally desirable. Apart from shortening lead time, this has immediate implications for sending colour information between colourists and the dye house or between clients (who may wish to specify their own colour palette to be used) and designers. Also, businesses often take advantage of reduced labour costs in other remote countries and hence have a requirement for wide area communication with their manufacturing plants. Yet another use is to replace the colourists' existing use of swatches or thread samples which are often gathered from trade fairs. Clearly, with the advent of low cost internetworking initiatives such as ISDN, ATM and the Internet, this sort of activity is likely to become much more commonplace in the future.

Out of the textile field, the precise reproduction and exchange of colour is also of concern. Examples include producing mail order catalogues and printing labels (both of which are usually required to closely match the main product). In general, not being able to produce paper hardcopy which even roughly resembles the screen appearance is highly frustrating for all computer users (hence the current boom in the sales of CMS software). As "work group" computing begins to take off, the exchange of documents or designs between users will become more important. This, too, would benefit from enhanced colour fidelity.

The tools that have been both proposed and implemented might also find use in education. In particular, colour notation systems are expensive to purchase in the form of a physical atlas. Furthermore, they are often hard to visualise owing to their cumbersome nature. Computer-based colour notation systems can be much easier to navigate and provide a convenient, integrated and cost effective means of exploring their colour space. The ability to interrelate between different systems is also a good way of comparing and contrasting the attributes of each notation. Some of the other tools such as the visualisation of metamerism, colour constancy, colour tolerance and colour contrast should also prove useful in the training of basic colour science principles.

7.3 ANALYSIS

To offset the numerous applications of WYSIWYG colour fidelity and communication, there are a number of limitations to the proposed approach. For completeness, these are now covered. In the ColourTalk system that has been described, there is no consideration of printer (or, indeed, any other non-CRT output device) colour gamut. This is in direct contrast to other conventional non-WYSIWYG colour management software. If a given colour falls outside of a particular imaging device's gamut, it cannot be faithfully reproduced. At best, only a close approximation is possible. The approach can lead to problems because the goal of achieving WYSIWYG colour precludes any gamut mapping or compression transformations. However, since the specific target device or media may not always be known at the time of palette or form design (or may even be changed later on), it is not always possible to transform colours at this stage anyway. Furthermore, output may be required to several different devices or media simultaneously (e.g. garment fabric and packaging) each of which has different gamut limitations. The dilemma of "achieving WYSIWYG colour" versus "making the best use of the available colour range" is only ever likely to be solved by the introduction of imaging devices having larger, less restrictive gamuts. Until then, gamut visualisation tools may prove useful in selecting realisable colours across a range of media. Clearly, for the present, when device gamuts are not sufficiently large for all applications, a choice has to be made as to whether a particular application requires WYSIWYG colour or not. For photographic imagery, a "pleasing" appearance is usually what is expected and WYSIWYG performance becomes less important.

The performance of this approach to colour fidelity is ultimately governed by its users. Periodic recalibration of imaging devices is required in order to maintain device independency. In addition, the viewing environment used needs to be carefully controlled to preserve viewing condition independency. In practice, many computer operators work in rooms flooded with highly variable ambient light. Persuading them to make all their colour-critical judgements in carefully controlled dimmed lighting conditions may be neither easy nor popular. Another shortcoming concerns the level of colour model integration. While the majority of the more popular colour notation systems are catered for, there do exist a number of more exotic systems such as DIN and Coloroid whose use would appear to be on the decline, although their implementation might still be of academic interest.

7.4 CONCLUSIONS

This work has drawn on a number of existing techniques to provide several unique features not presently found in current CMS or CAD systems. First and foremost is the notion of WYSIWYG colour. Many CMS products claim to provide good colour matching but in practice are unable to reproduce the same colour across different imaging devices. Part of the reason for this is a lack of consideration towards colour appearance factors (another unique feature of the proposed system). This is essential for cross-media colour reproduction or for any instances where the source and target viewing conditions are not identical. Having attained WYSIWYG colour, the next requirement is to be able to communicate it. This work has proposed integrating multiple computer-based atlas systems for colour notation and interconverting them mathematically (again, both of these features are not to be found elsewhere). Finally, a number of tools for colour control and visualisation have been suggested. Some of these have previously been available in isolation, but their combination is not to be found in any current CMS or CAD system.

Ultimately, this work has successfully demonstrated the way forward for colour management in colour computer systems. Its effectiveness has been proven in its embodiment in a system called ColourTalk which has been used for real colour-critical design tasks. WYSIWYG colour fidelity and WYSIWYG colour communication is essential to certain industries and is also highly attractive for less demanding applications. Limitations in current imaging technology means that WYSIWYG techniques are not suitable to all applications, however in such cases existing CMS techniques can still be applied.

7.5 FUTURE DIRECTIONS

Colour management is, at present, a very dynamic field. This may possibly be due to the huge investment that has already been made in CAD and DTP systems. Once further industrial trials have been conducted to verify their performance, the most logical next step is to incorporate these ideas for WYSIWYG colour into conventional colour management, DTP and CAD systems. This alone is not enough though; in parallel to this, users will need to be educated as to how to properly apply the technology (in particular, about correct viewing conditions and calibration procedures). For colour management as a whole, standardisation is an important goal. This should enable the free exchange of colour information, device profile data and matching algorithms between different systems. The introduction of a standard cross-platform profile format has already begun in the shape of the InterColor Profile Format (see §4.2.2). As imaging devices with larger colour gamuts are developed, the WYSIWYG approach to colour should become both more practical and more attractive. Until then, it may be necessary to create tools to enable users to visualise the limits of device gamuts.

Other areas of this work can be further expanded. As previously mentioned, coverage of colour notation systems is less than complete (although it can be argued that adding to the already bewildering range of available colour systems may only serve to confuse users). Further work might combine conventional CMS methods with the colour appearance techniques used here to perform gamut mapping or gamut compression in colour appearance space for those situations where it is necessary to cope with the restrictive colour range of certain imaging devices. Device characterisation can be further extended to consider a wider range of colour imaging hardware or model other coloration processes. Similarly, the colour appearance model used could be augmented to consider a much wider range of viewing conditions.

Chapter Eight

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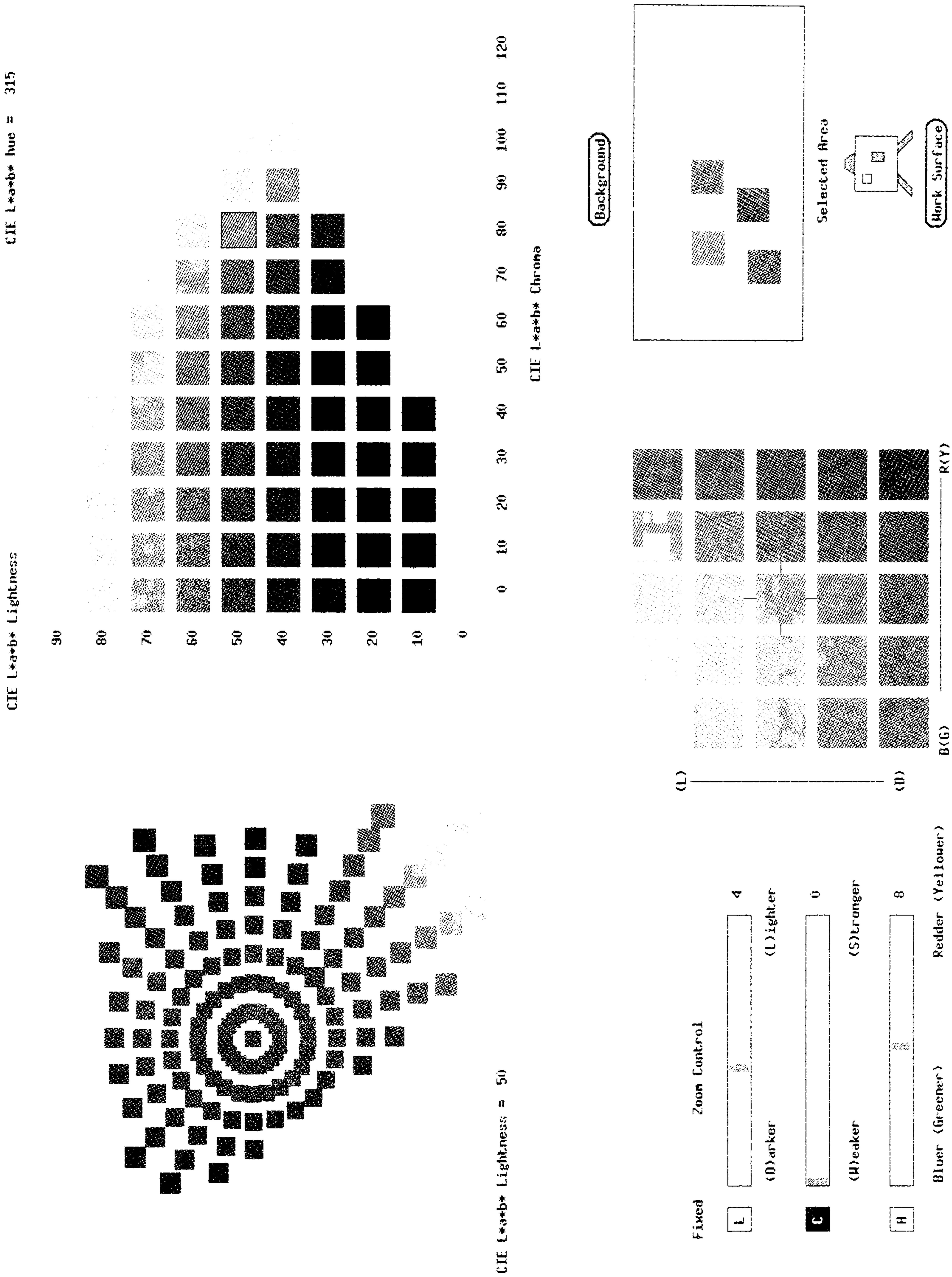
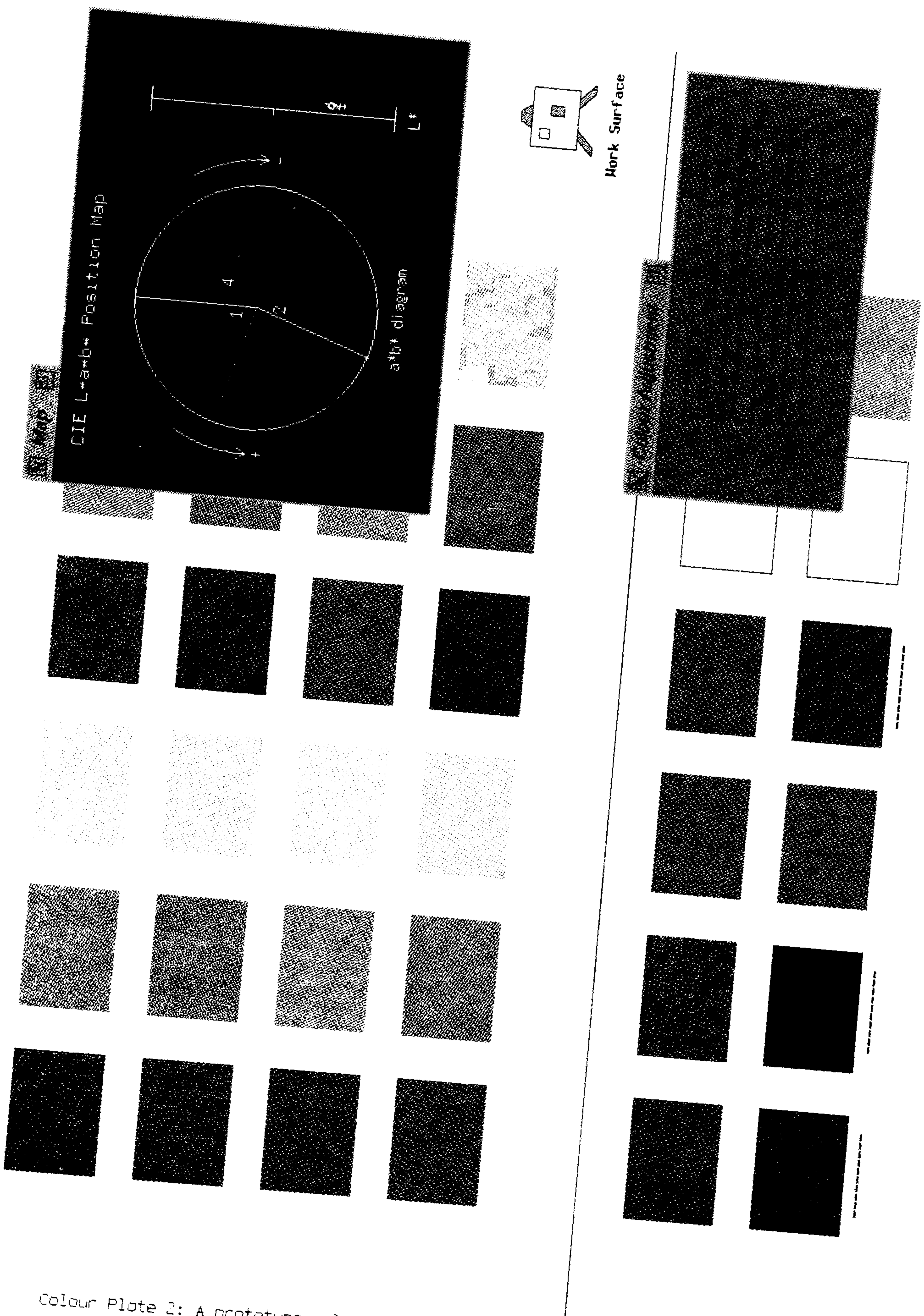
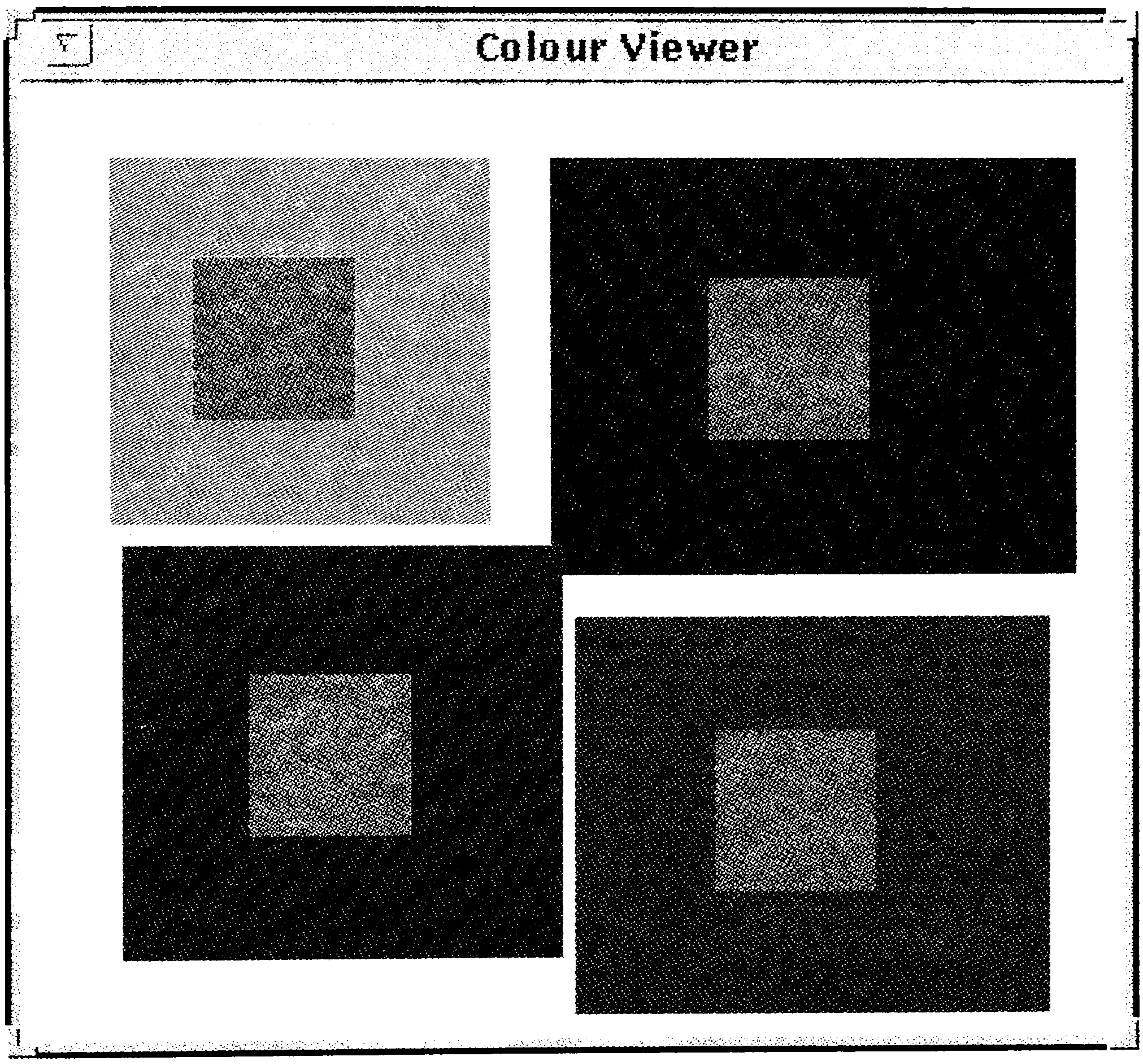
Colour Plates



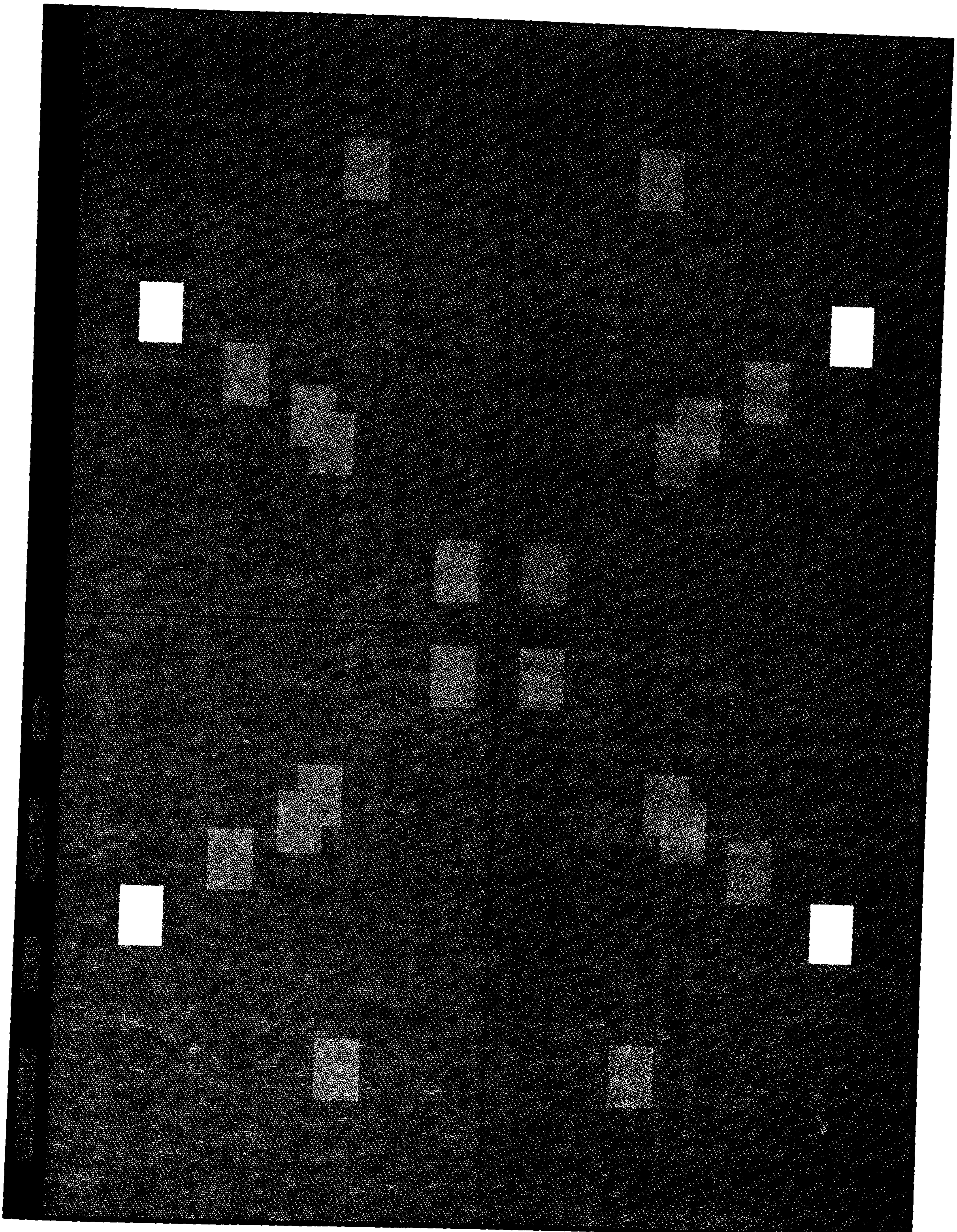
Colour Plate 1: Colour selection using CIELAB in the prototype system.



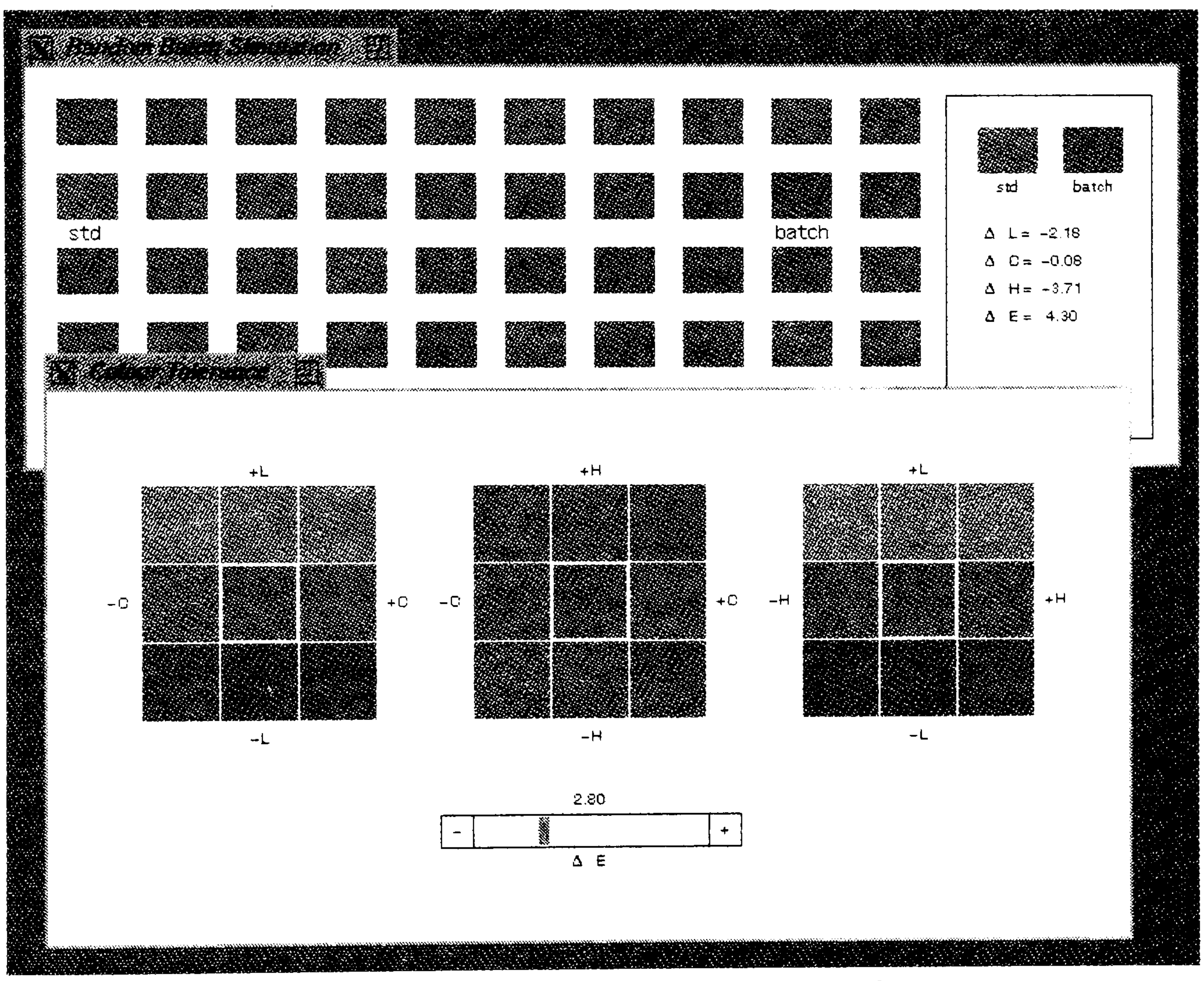
Colour Plate 2: A prototype colour palette (colours being adjusted darker).



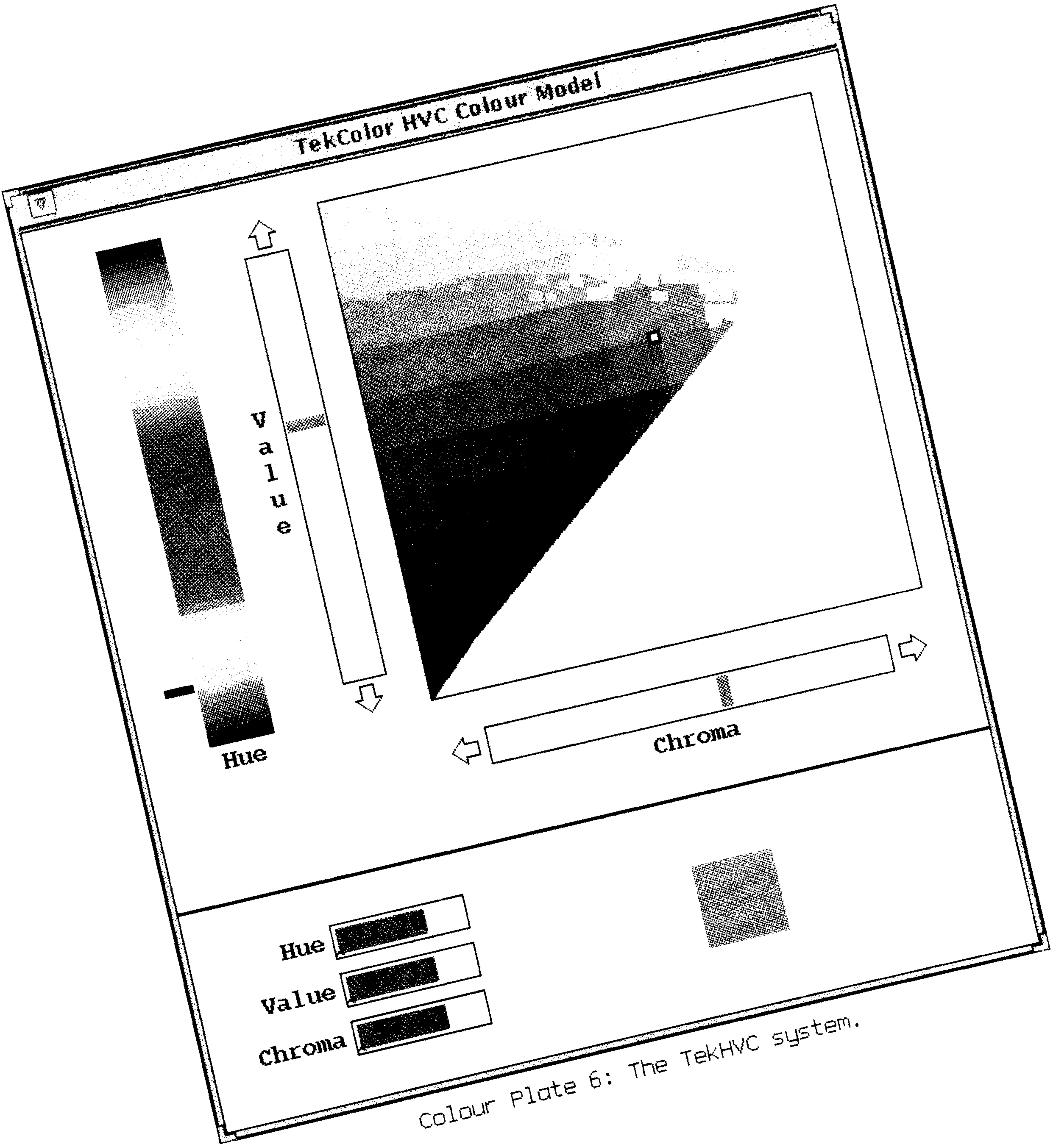
Colour Plate 3: Examining colour contrast effects.



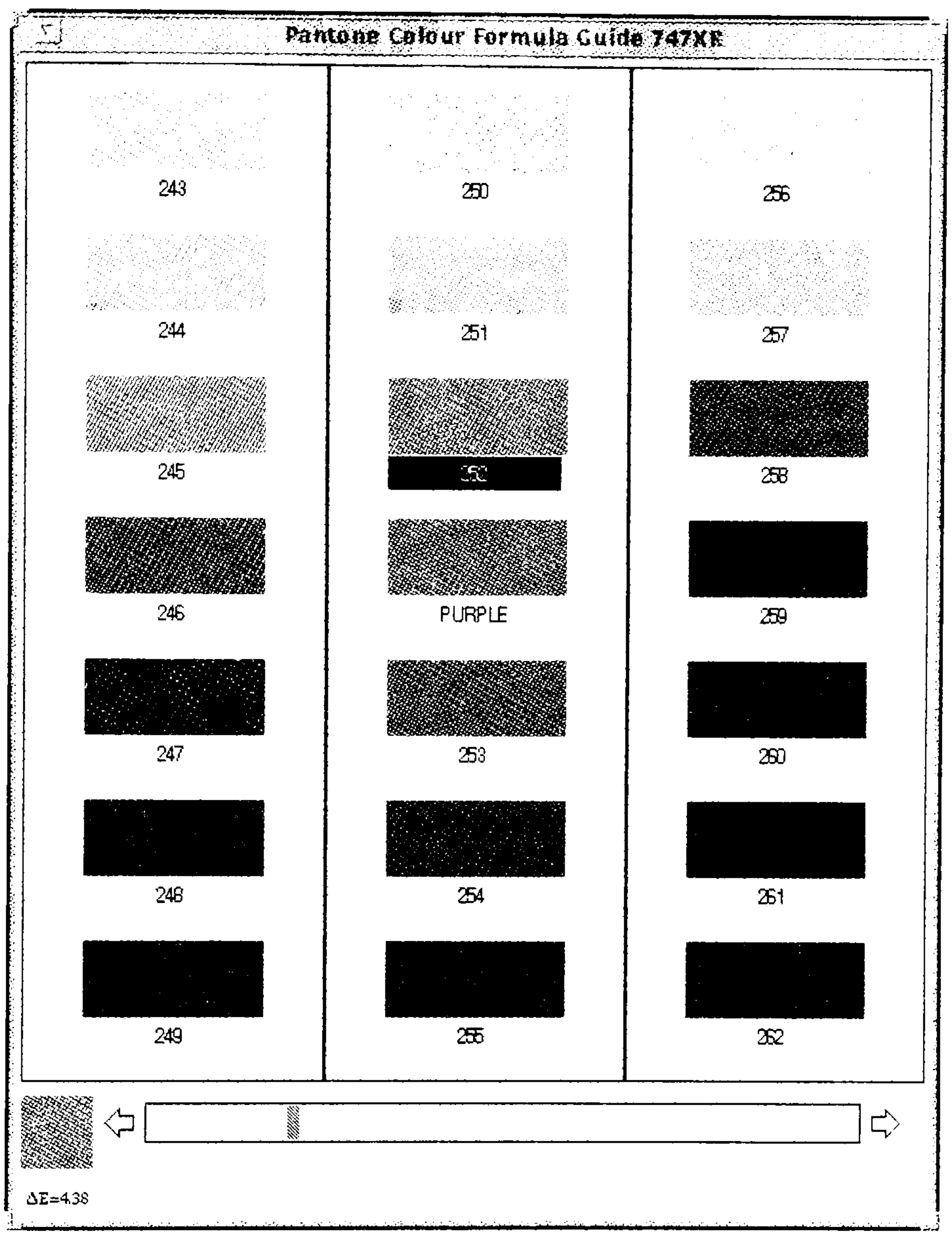
Colour Plate 4: Assessing colour constancy of dye recipes.



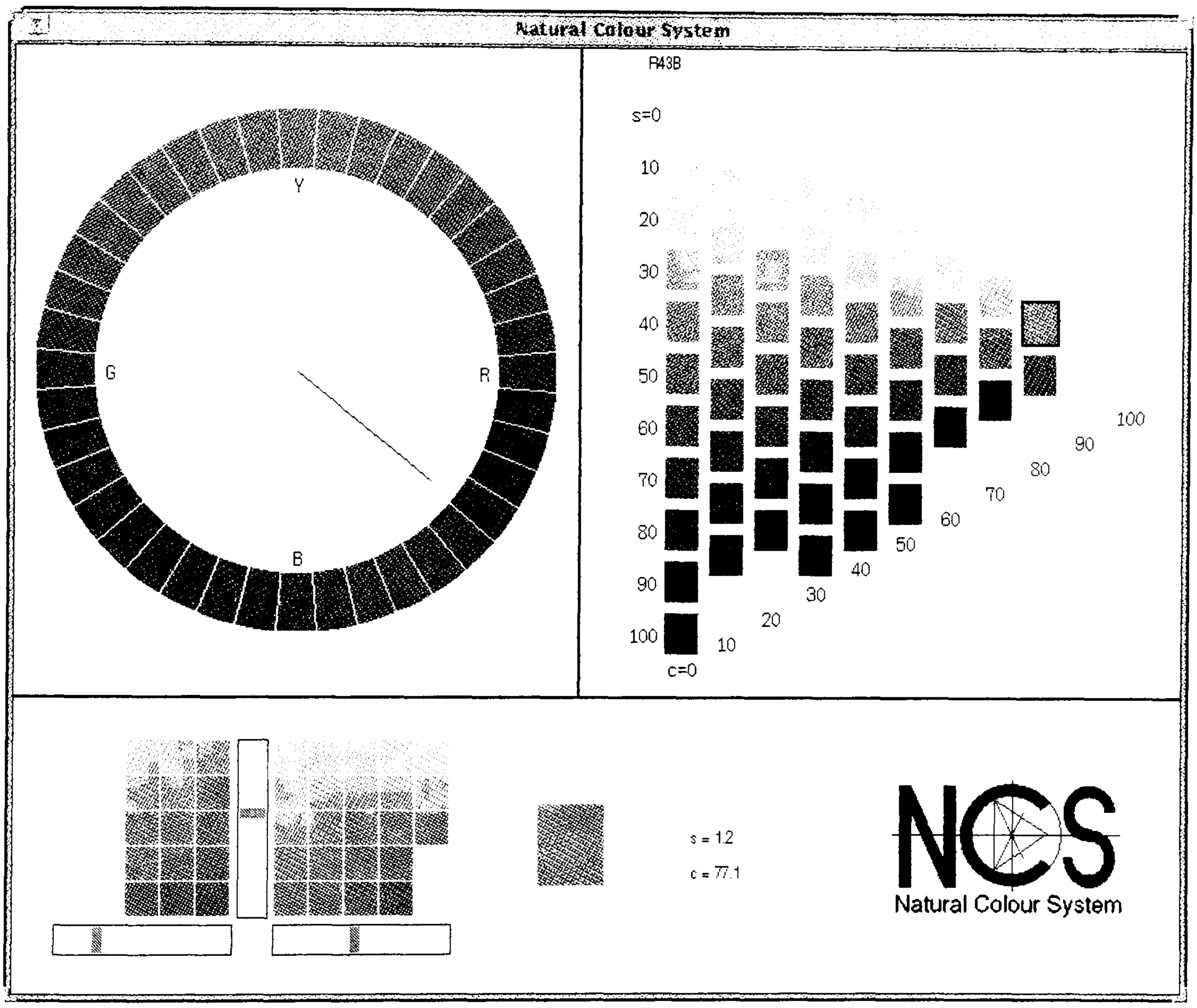
Colour Plate 5: Visualising the effects of colour tolerance.



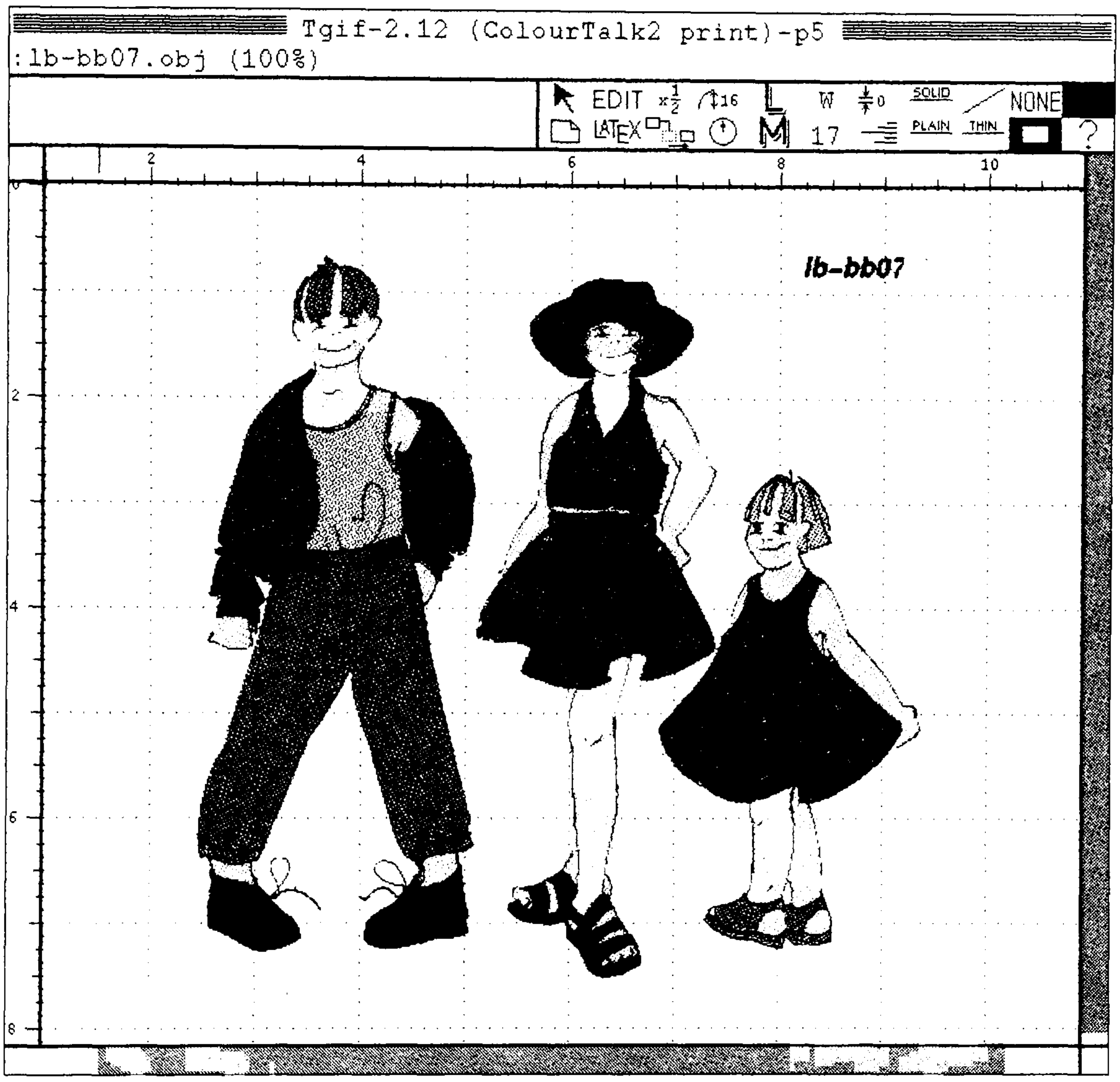
Colour Plate 6: The TekHVC system.



Colour Plate 7: Colour selection using the Pantone system.



Colour Plate 8: Colour selection using NCS.



Colour Plate 9: Basic design using ColourTalk.

Appendices

A: Design Visit One Report
B: Design Visit Two Report
C: Design Visit Three Report
D: Design Visit Four Report
E: Design Visit Five Report
F: Design Visit Six Report
G: Example DIN Calculations

APPENDIX A: DESIGN VISIT ONE REPORT

Introduction

Work is done one year ahead of the current season, with work throughout the year being scheduled according to a "critical path." Some additional development effort is ongoing throughout the year. Generally, the choice of colour is determined by a master *fashion palette* or is constrained by some other factors (e.g. career wear is usually required to be in company colours). The fashion palette is typically comprised of four ranges of colours: the *classics* (e.g. black, navy blue, white and red), *neutrals*, *bright* and *tonal*. The bright and tonal ranges will normally exhibit the maximum seasonal variation. Clients' fashion palettes may be used as references† when colours are adjusted. Exact fabric colours will later be "lab matched" to the palette. The purpose of matching colours to a *fixed* palette is so that customers in a shop can, without too much difficulty, buy separate garments that will closely match each other. During design, form and pattern are represented separately: detail and styling is done in parallel with fabric development. Most clients already have their own palettes, but where they do not, these are created *early on* in the design process and are subsequently used throughout for reference. It is possible that Pantone references may be used, but choices are not limited to this source.

The main task is concept design — producing patterns and samples, making a presentation and selling the design to a client. At the start of each season, the designers create their own *story boards* on a particular theme (e.g. "oil painting" might contain lots of bright colours). These are kept for reference purposes and are also shown to clients. Certain colours will be related to specific fabrics. While the colours in the story boards need not be *exact* matches, they will typically be quite close to palette colours.

The Critical Path

The *critical path* defines the activities for the design group for a particular season. These tasks are explained below.

† There may be a small degree of deviation from these colours provided that the palette fashion colours are predominant in the design.

- **Fabric Development** — done by the fabric designer who will visit various mills to *source* suitable fabrics. This process is ongoing throughout the year. Other sources include fabric fairs which are held before the start of each season. The world's largest fabric fair, *Première Visions*, is held every six months. This is organised into fabric types and suppliers will exhibit their new ranges. Sample swatches will be obtained, noting down any details such as supplier, composition, weight, width and price (so only what is required is actually ordered). The swatches are used later on by the designers to select which fabrics to order.
- **Business Strategy to Design** — strategy depends largely upon the success of sales (i.e. what has sold well) and provides an indication of what should be done as a business.
- **Design Review** — the purpose of this cycle is to provide feedback as to what has been successful.
- **Meeting with Client Design** — a team of around twelve designers from their client's company form a working party to put together a *colour range* (or palette). They get input from their key suppliers (which include *this* design group) and determine separate palettes for mens, ladies and childrens wear. The team provides not only colours but also predicted styles, fabrics and shapes (all such information is confidential to the designers' clients). The designers will then create their own *stories* (including styling and colour stories) from their client's design brief.
- **Market Research** — this involves the product-related interviewing of consumers at the client's stores and may involve any area (mens, ladies or childrens fashion). Its purpose is to give an indication of where to go next (e.g. where sales have declined or increased). Market research is carried out early on in the critical path to preempt mistakes.
- **Comparative Shopping** — a design team go to a specific shopping location (e.g. Birmingham, Nottingham or London†) to sketch information on each of the competitors products of a particular type that are on sale. The purpose of these visits is to produce a report on competitive products and compare these with those produced by the designers (on the basis of sales,

† London is not a typical area and is therefore not considered as representative.

colours, price, etc.).

- **Directional Shopping** — designers travel around the world (e.g. Tokyo, Paris, Milan, Amsterdam) to seek out new fashion or directions. They will look at expensive "high" fashion. Sketches are made of interesting design ideas that might prove useful for future work.
- **Develop Print Ideas** — the designers' own print ideas are produced on their own in-house CAD system. This work may also involve re-colouring an existing design into the fixed fashion palette colours. (The number of colours used in a particular design is quite limited, typically around twelve.) This is useful for screen printing and for demonstrating what is wanted. For example, showing what is required in "toning down" an existing print, rather than letting the print manufacturer do this (which would take longer and would introduce the potential for further mistakes). Using this system, paper designs (produced using a colour photocopier) can be given to the client for approval and thence to the fabric producers. Colour appearance is important for the CAD printing stage and designers will sometimes go as far as trying to reproduce texture on their printouts.
- **Sketch Reports** — these provide a summary of what was found during the directional shopping trips. It usually takes one week to produce such a report.
- **Mill Visits and Range Previews** — these give an indication of any new fabrics that are likely to become available. The mills provide the designers with fabric swatches in a selection of colours. Some of the more important mills may produce a range preview (which may not be the full range), however a decision to order is not normally made until after Première Visions when the designers are able to see what else is available.
- **Product Strategy** — for each division within the designers' group, product strategies are devised. These form a checklist indicating the current state of affairs: e.g. what orders there are and what actions are necessary to take on business. Note that this strategy is for a *specific* product, and not for the complete design work.
- **Sketches for Ranges** — these are based on the designers' ideas, comparative shopping and any other sources. Sketches are made and organised into either fabric type or price area. Many

sketches are produced (usually quite simple and in black and white) and some from each area are chosen. From these, more elaborate sketches and fabric boards will then be made.

- **First Patterns, Toiles, Costings** — patterns are cut to make mockups which are used to preview the patterns. Initial costings will also be done for the most "difficult" items.
- **Design-Review Sketches and Consider Lessons Learned** — a review is held of what has been produced so far. At this stage, certain items may be rejected if, for example, they cannot be costed.
- **Present Sketch Boards to MDs** — sketch boards illustrating the completed designs are shown to the managing directors of the design group's clients.
- **Première Visions** — fabric show held in Paris (see *fabric development* earlier).
- **Departmental Briefs** — each individual department of the client's company (e.g. "skirts") will announce their intended plans. Both business strategy (internal) and product strategy (external) are discussed; their manufacturers are told which items have sold well.
- **Individual Briefs** — the client's departments discuss specific areas with *this* design group. Unlike the departmental briefs (which are to *all* of the client's suppliers), these meetings are held with just one supplier.
- **Produce Samples** — one off samples of complete garments in the final fabric are made in order to build up a range for presentation.
- **Internal Range Presentations** — an internal presentation is held for the design team, sales team and MDs so that they can all see the proposed products.
- **Range Presentations to Departments** — a fashion show is held in London (with models) to present the designs to the client's departments.
- **Review Strategies** — the product strategy is studied to determine whether any change is required.
- **Development** — this can be viewed as a process of *refinement* (i.e. the "icing on the cake") which commences after the core design work has been completed. To this end, some of the

earlier processes will be repeated. Some forward-looking designs that might catch the eye of their client will also be considered.

Choice of Colours

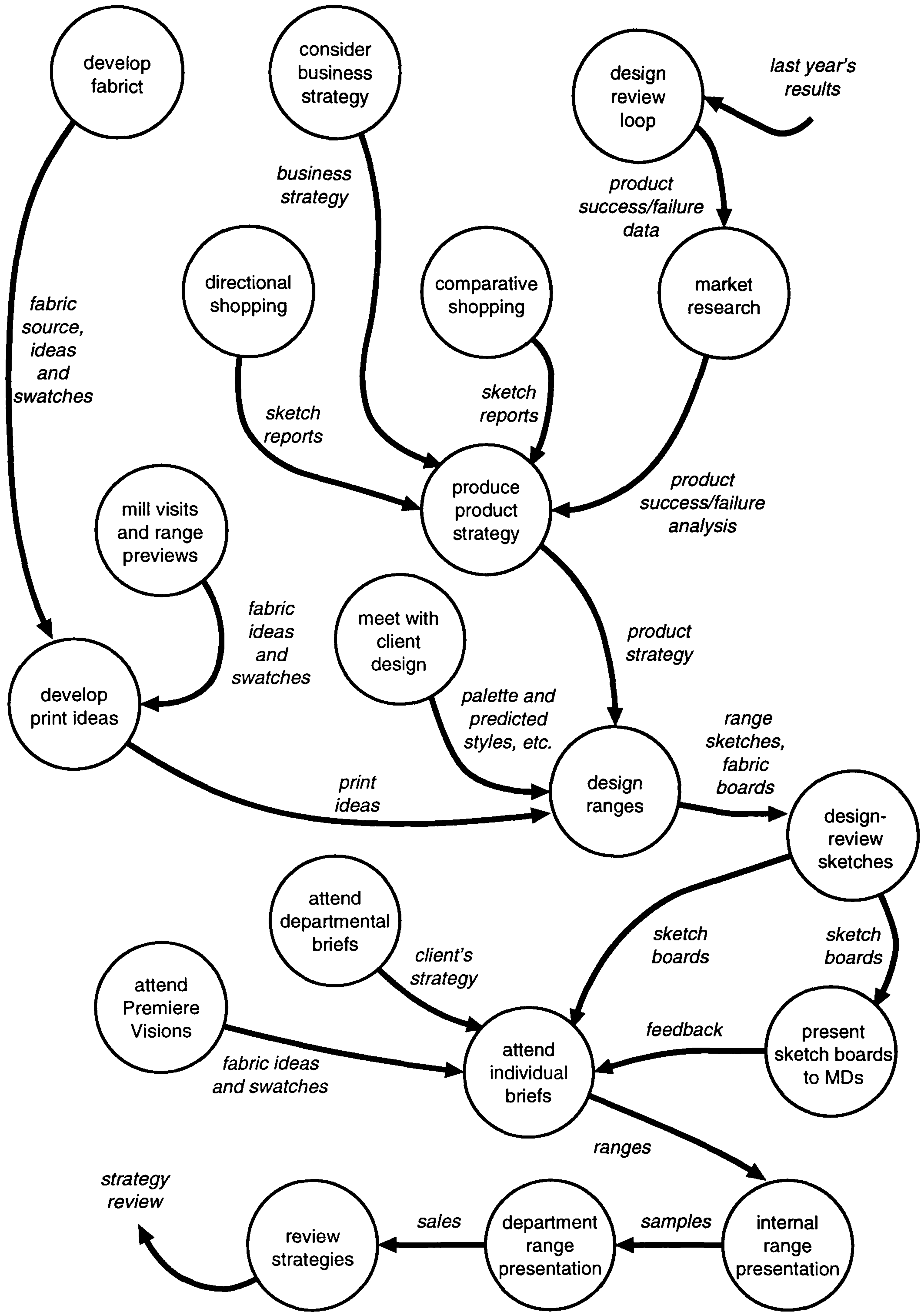
Colour palettes are developed as a result of a seasonal fashion forecast. (However, note that career wear is not seasonal.) Each area (childrens, ladies and mens wear) will have separate palettes. Where the design is not constrained to a pre-determined fashion palette (as is the case with their main client), the designers may be asked to select colours for their client. The client may have certain colours in mind or may just let the designers choose for them. The choice of palette colours is generally a cooperative process. Figure A-1 provides a dataflow diagram illustrating the main processes on the critical path along with their major inputs and outputs.

Computer Aided Design

The designers use a Silicon Graphics workstation running a software package produced by a company called CDI. A colour photocopier is heavily utilised for the communication of designs as this makes rapid visualisation via the production of mockups possible. With their system, they are able to scan in designs directly from the hangers† or from fashion magazines. Using the CAD software, they can then clean up and resize the design. Once scanned in, images can contain many thousands of colours. For most designs, approximately twelve are sufficient. The *flattening* (colour quantizing) and eventual recolouring of designs to the client's palette is a very laborious manual process. With the CDI software, it is also possible to produce a pseudo-three dimensional simulation of completed designs. This is accomplished by manually contour mapping an original image (of, for example, a white skirt). The design is then mapped onto this traced image. The system also permits *tinting* (colourising) of scanned images: a translucent colour is applied over a certain area of an image. This has the advantage of preserving the shading of the original image which then adds to its realism. However, because of the time taken to produce such images, these latter two

† These contain one square foot of fabric swatches which are produced with bulk orders and are retained for future reference purposed.

Figure A-1: Dataflow diagram showing group design processes and products



facilities are rarely used.

With their system, the designers also produce suggested art work for packaging. These are printed out and stuck onto actual cartons. This allows the *whole* design to be shown in presentations and is essentially done to give their customers a better picture of what they are buying.

Conclusions

Computer simulation and mockup saves the expense of having real samples produced. Use of the computer and colour photocopier also makes it easier to "borrow" ideas from other sources. Although the story boards only approximate the final colours, exact matching will eventually need to be done. It was felt by the designers that it might be better to match earlier on to avoid misjudgements of colour coordination. There were four specific issues arising which relate to this work:

(1) Only a very limited number of colours are used in the final design.

(2) Colour selection plays a very minor role in these designers' activities (since their major client controls the colours which are used).

(3) colour fidelity/reproduction is *very* important, especially since paper is being used as a communication medium. A lot of effort is spent by CAD system operators trying to match printed colours to screen colours.

(4) The design process (but not necessarily the actual design work) is highly cooperative. It involves many different media and activities in different locations. At present, the use of CAD plays an important but limited role in the design process.

APPENDIX B: DESIGN VISIT TWO REPORT

Introduction

This report summarises an interview with designers whose work involves anticipating what their customers (who are garment designers) will produce. The direction of their activities is affected by both the weavers and the garment designers.

The Design Process

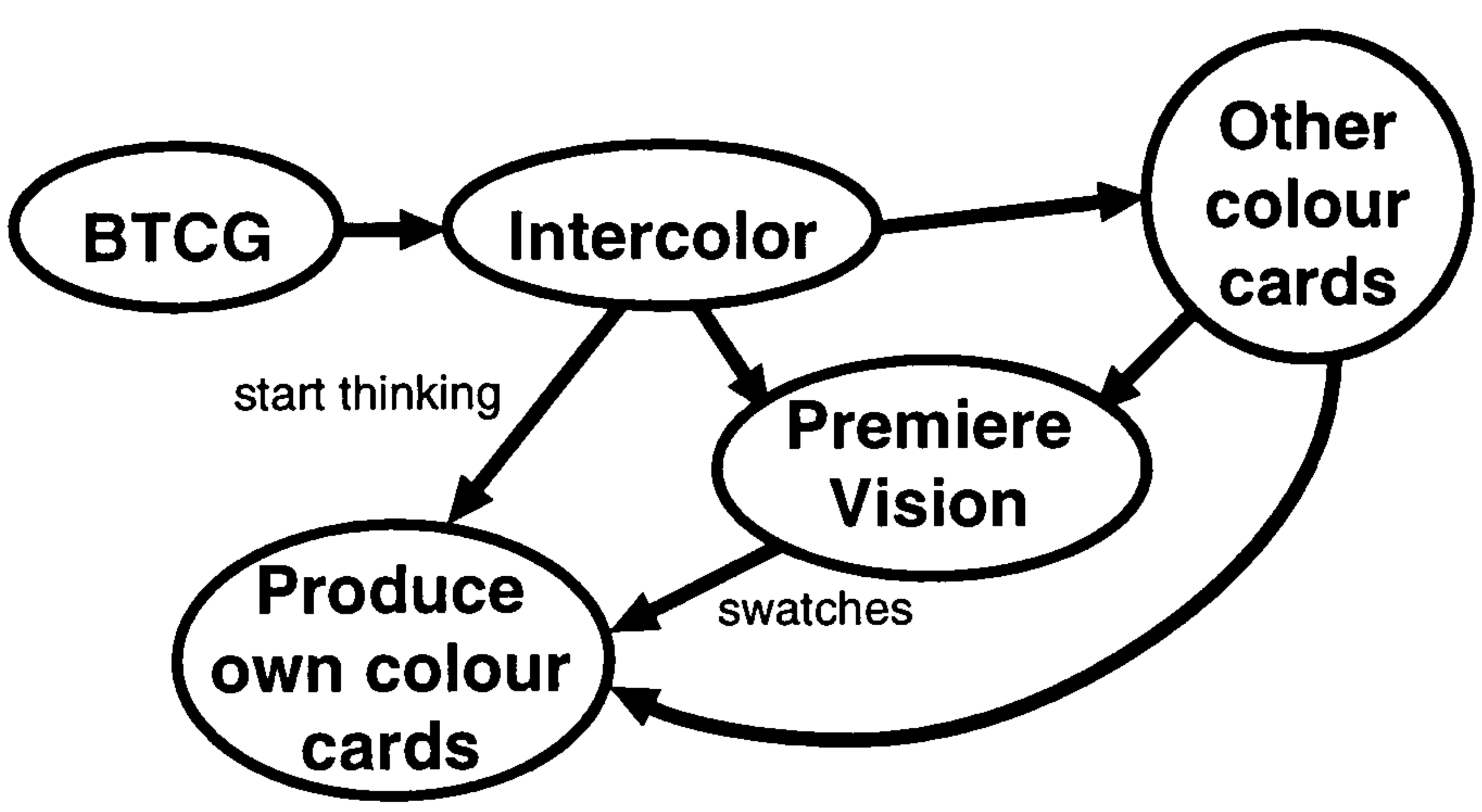
Work is done approximately two years ahead of the current season and involves input from the designers at all stages. The main influence in apparel trends is the *Première Visions* trade fair. This fair is divided up into fabric type (e.g. wool, silk or lace) and involves only European countries (i.e. not Japan or the USA). It is attended by fabric designers and garment manufacturers who are looking to this event either for direction (via sampling) or as confirmation of their own thoughts. (Note that fibre type influences the choice of colour and determines what colours can practically be produced). Most countries have government- or industry-sponsored bodies to disseminate colour information to their customers, such as the *Deutsche Mode Institut* in Germany. However, there is no longer such an organisation in this country. (All that remains are the British Colour Council archives, which are held at the Royal College of Art.)

Instead, what happens is that several UK organisations (including ICI, the Wool Secretariat and any others that need to work in advance of the current season) hold three meetings per season in order to put together a colour card. This group is known as the *British Textile Colour Group* (BTCG). They will begin with ideas presented in various forms such as yarn, paper or wool. Their output is represented at *Intercolour* which is an international meeting held twice per year and attended by about twenty-five other countries. As well as producing an *international* colour card, it is an opportunity for attendees to see the other twenty-five countries' cards. The international colour card is of limited use, however, as most countries have their own nationally popular (and unpopular) colours, and so national institutions will distribute cards with colours based on this that satisfy their own country and company. Intercolor is useful because from it trends begin to emerge and it enables the designers to start thinking about the direction of their work.

Although Intercolor is two years ahead of the current season, the fibre suppliers work even further in advance. Decisions for wool are made by the *International Wool Secretariat* (IWS). Because of the timescale involved, the occasional adjustment must be made to their planning; but the production of wool is, on the whole, less volatile than other fabrics.

As well as these, there are colour cards produced by other sources such as Cotton Incorporated (USA) or CIBA-GEIGY (dye industry) in a variety of media (yarn, wool, fluff, woven material, paper) which are for the use of their customers (i.e. fabric producers and styling services such as Peclers and Trend Union). All of these cards will be used as reference during the designers work. Several seasons may be worked on at once, each being at different stages of development and presentation. The cards are used to show which colours and on what sort of fabrics they envisage being used in a particular season. Their ideas are presented on boards comprised of colour cards, cloth samples and images suiting the overall *story*. These are shown to their own company and individually to apparel customers. The presentations will demonstrate conceptually how colour can be used within each division (outerwear, lingerie, etc.), though they have no power to *make* the company produce any of the recommended fabrics. The flow of information throughout this process is illustrated in Figure B-1.

Figure B-1: Information Flow



There are two colour "standards" in use by the designers: the Pantone textile (cotton) colour selector and SCOTDIC (Japan). Pantone is sometimes used for colour communication, whilst SCOTDIC was found to be useful for making up colour cards — customers like to buy from colour cards made using the actual fabric. Another system in use is the JAFCA (Japan Fashion Colour Association) Basic Colour Code; this provides them a scheme for colour naming. An interest was expressed in the accurate electronic communication of colour. Design work is supported by a CAD system; its use involves matching existing thread palettes via sample colours printed on either of their thermal or inkjet printers.

APPENDIX C: DESIGN VISIT THREE REPORT

Introduction

The designers interviewed here are responsible for the selection of colour palettes. A summary of their design processes is now given.

The Design Process

Development is done fifteen months in advance of the current season and work on colour is begun early on via the British Textile Colour Group. The BTCG holds four meetings per season, with the first of these concentrating on feedback from past efforts. During the following meeting, ideas for the new season are presented. The later meetings will be influenced by the outcome of international meetings.

There are two main starting points for colour selection. The first is searching through magazine archives and pulling out images that in some way seem appropriate or are new and can be formulated into a colour range. For example, pictures of stonework might be used in producing a range of neutrals. Not everyone works back very far and some use images taken from books. Another starting point for colour is to examine the *evolution* of colours based on the previous seasons' palettes. In particular, which colours were popular, have been developed and at what rate. It was felt that the process of colour selection is quite subjective† and not necessarily directly relevant to current fashion: any image source could be appropriate.

The next stage is to get hold of suitable yarns in colours matching these images. In order to meet BTCG approval, it is important that these yarns be *sourceable*. That is, the yarn reference number can be quoted and samples easily obtained for various types of yarns (e.g. thin silky cotton, wool or linen). The type of colour chosen does determine the type of yarn that is both suitable (i.e. does the best job) and available. The buyers prefer to see colours in yarn form because of its textile appearance (they find it easier to relate to this form than paper).

Colours are categorised into either *levels* having the same "colour depth" (e.g. darks, lights and mid-

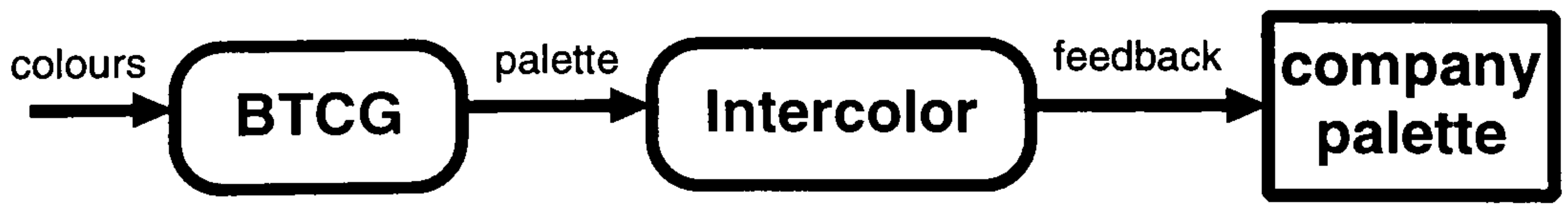
† However, ideas *are* compared with other people and there *is* some level of agreement made.

tones) or *families* (e.g. greens). Often, there are no sets of families borne in mind when starting colour selection but these are later developed because they are important for the final presentation. Therefore, it is important that the colours work well together as a whole. Presenting these colours at the BTCG meetings produces feedback as to what are likely to be the important areas of colour, indicating what should be developed for one's own market needs. The BTCG palette will be represented at Intercolor for consideration on an international basis. The overall outcome of these meetings is a group palette for one particular area (e.g. menswear).

At this company, colour palettes will be developed to suit their own requirements. Generally, this is done by analysing trends using appropriate imagery and by collecting sample garments, fabrics and colours relevant to the working palette. The exact details of this process differ according to the designer and are confidential information. From these palettes, colours are chosen and put together with other colours taken from past season's palettes which are deemed as still being suitable. Again, yarns will then be sought and an initial CAD palette (a "close" representation to the real colours) will be produced. This will then be supplied as a document which can be taken away by their buying departments (who also usually prefer to take snips of fabric or yarn samples).

At the same time as palette design, work is undertaken to consider trend directions as a whole (fibre types, fabric, pattern, garment styling, etc.). This is so it can be seen which colours can be applied and in what combinations. Other companies' garments are bought-in to illustrate the various aspects of what is required — perhaps having the right colour, fabric or style for the image that they are trying to create. Also, by shopping around, a *formula* (or theme) will be generated and picture/story boards will be produced to illustrate it. A very much simplified overview of the process of colour palette selection is illustrated below in Figure C-1.

Figure C-1: Overview of Colour Palette Selection



Whatever the means by which the design process is to be conducted with in the future, it is a requirement to eventually see the colour on fabric. At present, they have a colour technology department who arrange all lab dyings. Having tried another computer-based system for colour palette design, it was felt that computers could play a useful role in this process.

APPENDIX D: DESIGN VISIT FOUR REPORT

Introduction

A summary is presented of a visit made to designers from a company that designs both fabrics and garments for only *one* client. As such, they are privy to more information than some of the client's other suppliers. Throughout their work, there is a trade-off between time and volume versus accuracy.

The Design Process

Design work is divided to two seasons (Autumn-Winter and Spring-Summer) and also into two areas: childrens and mens wear. Mens fashion colours tend to remain the same whilst the colours used in childrens wear tend to change from season to season. Design teams from each of the client company's departments (mens wear, childrens wear, etc.) may make fashion predictions (including colour). Their sources are trade fairs such as Première Visions and also other organisations such as the Cotton Council and the Wool Secretariat. Meetings are held in which supplier and customer discuss *colour stories* for potential products. Once these colour boards are agreed upon, it is undesirable to make any further changes. Colours are often grouped into *families* (e.g. "neutrals") within the final palettes.

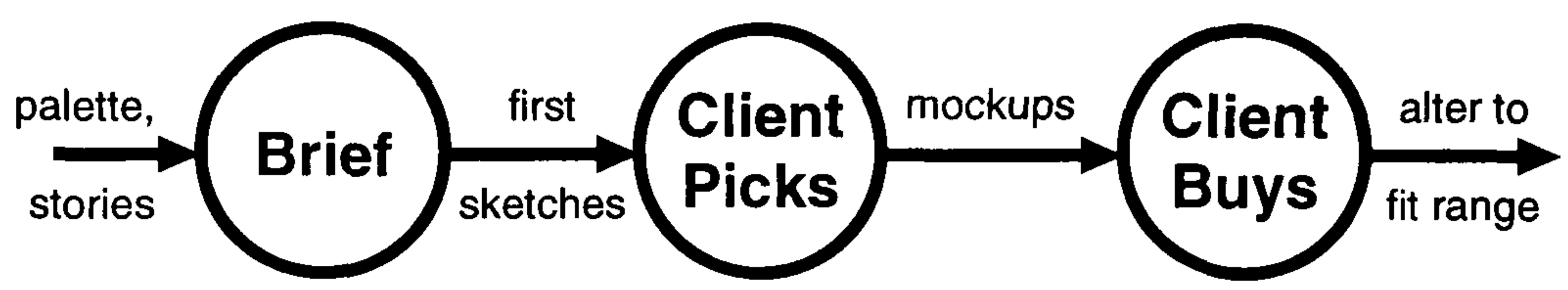
Black and white (line art) designs will be made and these designs will be used in repeat. Since manual replication can take considerable time and effort, a black and white photocopier is often used. It is much quicker to work in black and white before eventually scanning the designs into their CAD system and colouring them up. There was a strong feeling that any design work done *directly* on the CAD system was too constrained and a waste of valuable time and resources. Work is done with just the *form* ideas in parallel with fabric ideas, bearing in mind the garment type. The garment type is particularly important in the design of boxer shorts, for example, as the design has to work within the limited display area of the presentation pack. Their CAD system proves to be most useful to them in the areas of presentation (or product) visualisation and in the production of the final selected designs.

Design ideas come from directional and comparative shopping and shows. Fabric, garment makeup, price, etc. will be analysed in order to produce a report. This is used to establish a pricing/selling structure.

The initial form of the palette is thread samples. Ranges will be designed based on these palettes. However, it is not until most of the design work has been done that the final palette for a season is distributed in fabric form. After buying and before the final printing, exact final colours will be agreed upon.

The design process usually involves the following. First, a strategy for the target season is established. Meetings are held in which the sales performance of various products will be discussed and it is decided what should be developed; the meeting is primarily concerned with financial matters. This presents a broad statement about the product strategy of the company. The outcome of these meetings determines the structure of the proceeding design work, given that many designs will need to be produced. A few weeks after this meeting, the design team will make a presentation of design ideas to their clients. Complete garments or mockups (possibly just a presentation pack) will then be made for final selection. Any one of these stages may elicit changes to the designs. The entire design process is summarised pictorially in Figure D-1.

Figure D-1: Summary of the Design Process



Although the CAD system was clearly limited in its usefulness because of the time taken to do actual design work using it, it was felt that it would be useful to be able to link it to their existing paper, pen and photocopier system. Also, some facility for auto-repetition of designs would be labour-saving (however, it would have to be at least as convenient to use as the photocopier). Currently, operation of the CAD system is not done by those producing the designs. After their designs are presented to the operator for scanning and colouring there is little or no time for further discussion of the design and once scanned in, usually no change is made to the form (printouts/artwork must be correct before scanning in).

It was felt that the overall standard of design has improved due to the increased facilities enabling better and easier realisation of complicated designs (which may not have been attempted previously due to their difficulty). Colour adjustment is particularly easy using the CAD system (e.g. one is able to produce the same design using different shades) however form adjustment is much less easy and so is still done conventionally. Only basic designs (such as spots and stripes) are attempted using just the CAD system.

Using the CAD software, designs are scanned in greyscale. Once scanned in, a simple (user-selectable) binary threshold is applied to reduce the design to monochrome. The resulting image may include some "noise" which will have to be manually eliminated. If the design has been selected, the image will then be colourised to palette shades using the CAD system's paintbox. (The software supports both RGB and HSV colour systems and the next release is expected to provide an automatic flattening capability.) The current system provides text facilities which are used for producing wording in motifs, etc. and it is also used at great length repeating patterns, stripes, etc.

Output of finished designs is to a thermal wax printer. Correspondence between screen and printer colours is determined using a "colour catalogue" which is produced by printing out regular grids of colours and then matching these to palette colours. A reasonably good match is sought where the samples are being used to give an overall idea. The CAD final image is used in making a (fabric) print of the design. All colour matching is done to paper, since this is how the designs will be presented to the buyers.

APPENDIX E: DESIGN VISIT FIVE REPORT

Introduction

This report summarises a visit made to a design group that, again, produces leisurewear almost exclusively for a single client, with the remainder of their work being for one other client.

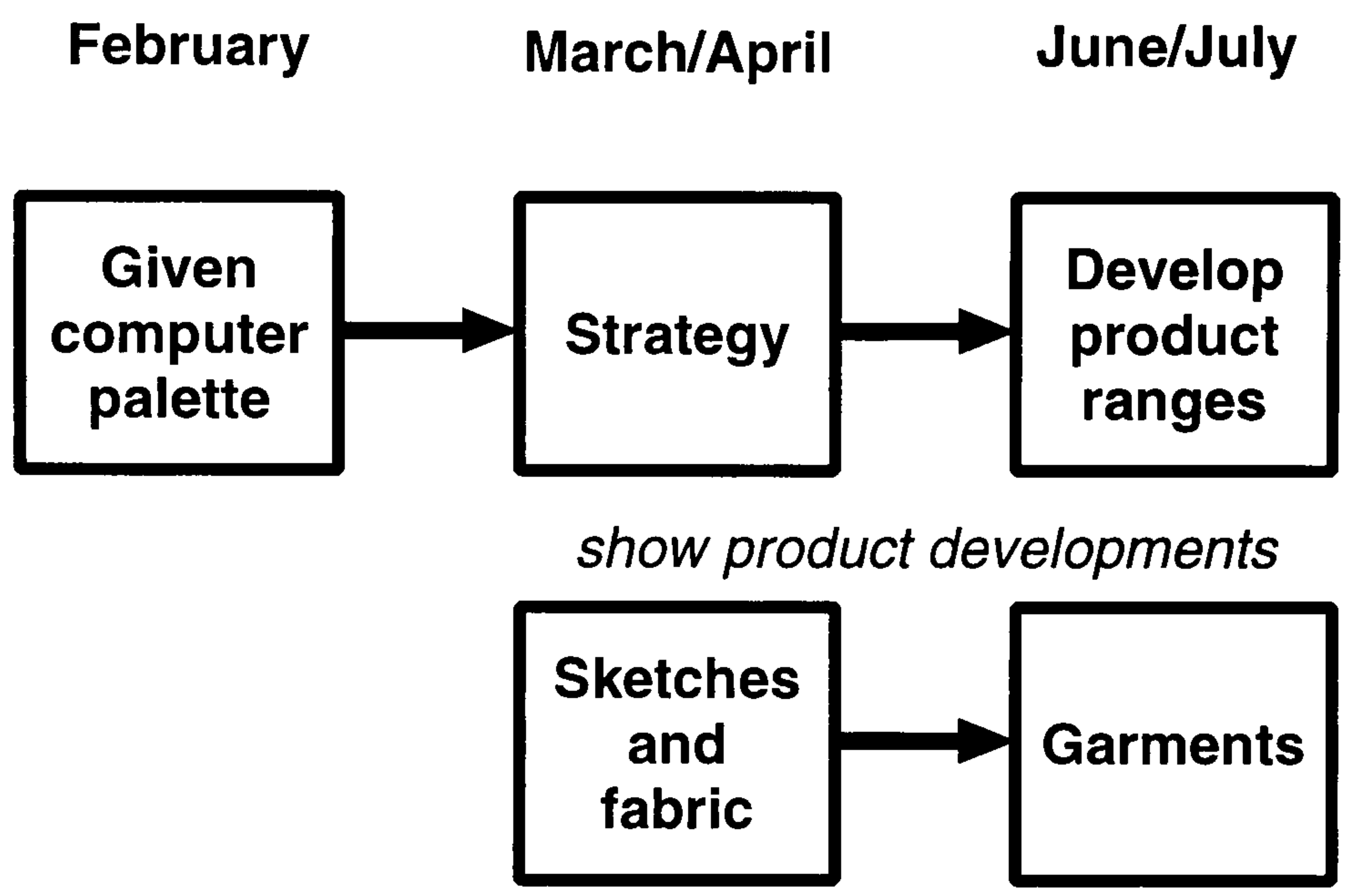
The Design Process

Design work is done one year ahead of the current season and begins upon receipt of the customer's palette. The designers' own *colour views* are then put together, however they are predominantly guided by their main client's strategy. This process is not helped by the difficulty and time taken in getting hold of their client's palette. The initial palette is supplied as a computer hardcopy; as the printer's output quality is quite limited, it can only be regarded as an *approximation*, thus providing the designers with an *indication* of the required colours. It is not until two or three months later that the final palettes come out on fabric patches. However, at this stage, they are normally definitive. From the palette, specific groups of colours will be used at different times during the season.

Once the computer palette is received, their own strategy will be devised to determine how each of the colours will be used. At the same time, they will visit fabric shows in order to get samples in the relevant colours. As the detail of the client's palette becomes more well defined, it becomes easier to get hold of suitable fabrics. At this stage, attention will be more focused on the actual colours and these will be illustrated through the use of either Pantone or a close computer match. Also, print development will be done and a strategy meeting will be held "around the colour" with their client.

Their client will hold initial departmental briefs to all its suppliers. Information exchanged at this stage will be very basic and will concern such things as colour and price. Each supplier must then prepare their own (commercial) strategy. This is the design group's opportunity to present what they feel their strategy should be. Prior to this, a visit will be made to other designers for their predictions in colour and fabric. The strategy is devised through a series of internal meetings. The presentation will be supported with *theme boards*, *silhouettes*, samples (which have to be specially bought) and sketches and will also include pricing detail. Types of fabric may be suggested but the colours used are essentially those in the client's palette. During this meeting, their client will tell them what they think should be developed. After this, another presentation of sketches and garments will be made. A typical sequence of events is depicted as follows in Figure E-1.

Figure E-1: Simplified Design Activity Timetable



During this time, fabric development is ongoing but is largely influenced by Première Visions. Print design may be done internally (there are ten print designers within the building) or freelance work may be bought in. Whatever the source, their CAD system will be used to make an illustration of it by scanning in the print and recolouring it into the client's palette colours. This group is somewhat unique in that it is the designers themselves that use the CAD system and not specially trained operators. Ideally, more emphasis would be placed on the CAD system, however it is time-consuming and is limited by the poor fidelity and speed of their colour printers. To overcome this problem, the designers work from paper (output), knowing that what they see on the screen is not quite right. All judgements concerning colour are made by eye: there is no objective colour measurement.

In the future, the design group hopes to purchase a new printer, however at present they have to make do with a resolution of only 4,096 colours out of the monitor's range of over 16 million. As the output is to be used as part of presentations to their customers and also used in their own decision-making process, it is important that their new device has high print quality, clarity (240 to 300 dpi) and a large gamut of available colours. Being able to print to other media, particularly cloth, is seen as being advantageous. The new printer would also have to be reasonably fast, unlike their present system.

Due to the high sampling costs, it would be preferable if they did not have to make fabric samples for complete garments and could instead use paper. To make this possible, the CAD system should be able to reproduce the appearance of the final fabric. Since their client's buyers would probably still prefer to see actual garments, the designers would at least like to be more certain of the outcome before going to the expense of having *strike offs* produced in a particular *colour way* (choice of colours). It is anticipated that in the future, a quick response time will become increasingly important and it is hoped that much of the wasted time will be eliminated by getting exact palettes to enable the designers to work closer to the final version of the product. It would also save time if palette and dye recipes were produced at the same time and distributed electronically. It is believed that much of the redesigning activity that goes on is due to insecurities with the colour palette.

APPENDIX F: DESIGN VISIT SIX REPORT

Introduction

This report summarises a visit made to a design group who, once again, design lingerie exclusively for one customer. As there are many similarities between the design process here and at some of the other design groups mentioned in the earlier reports, only the main differences or additional things learned will be discussed.

The Design Process

Work is done one year in advance of the high street. As a group, however, their work begins at the various yarn fairs and this may be done up to two years in advance. Design is influenced by visits to international fairs (e.g. to collect bedding or towels), external influences and production (e.g. new techniques). Outside influences include outer wear fashion,† expositions, some other significant event (e.g. the anniversary of the death of a famous artist) or just whatever looks interesting. These factors are used to suggest themes and colour ideas. The themes themselves are actually quite limited within night-wear (e.g. flowers or spots) and so there is not much variation in colour from season to season — mainly just pinks and creams.

The themes are presented on *mood boards*. The mood boards do not consider form. These are produced and shown along with samples to chief executives (internally) and then subsequently to their client. From these, it will be decided what is to be produced. Their client's selectors will also have a picture of what themes are current and appropriate (although they do not choose high fashion). Only a small range of colours are shown and these do not need to be exact, just general ideas. In order to meet with the client's approval, the client's palette should eventually be matched exactly. There are some difficulties in matching to this palette as it contains samples cut from different types of fabric, each having different texture (which therefore affects colour appearance). The lingerie palette is smaller than — but created in conjunction with — the outer-wear palette. This is to ensure continuity over all the client's garments. Unlike other design

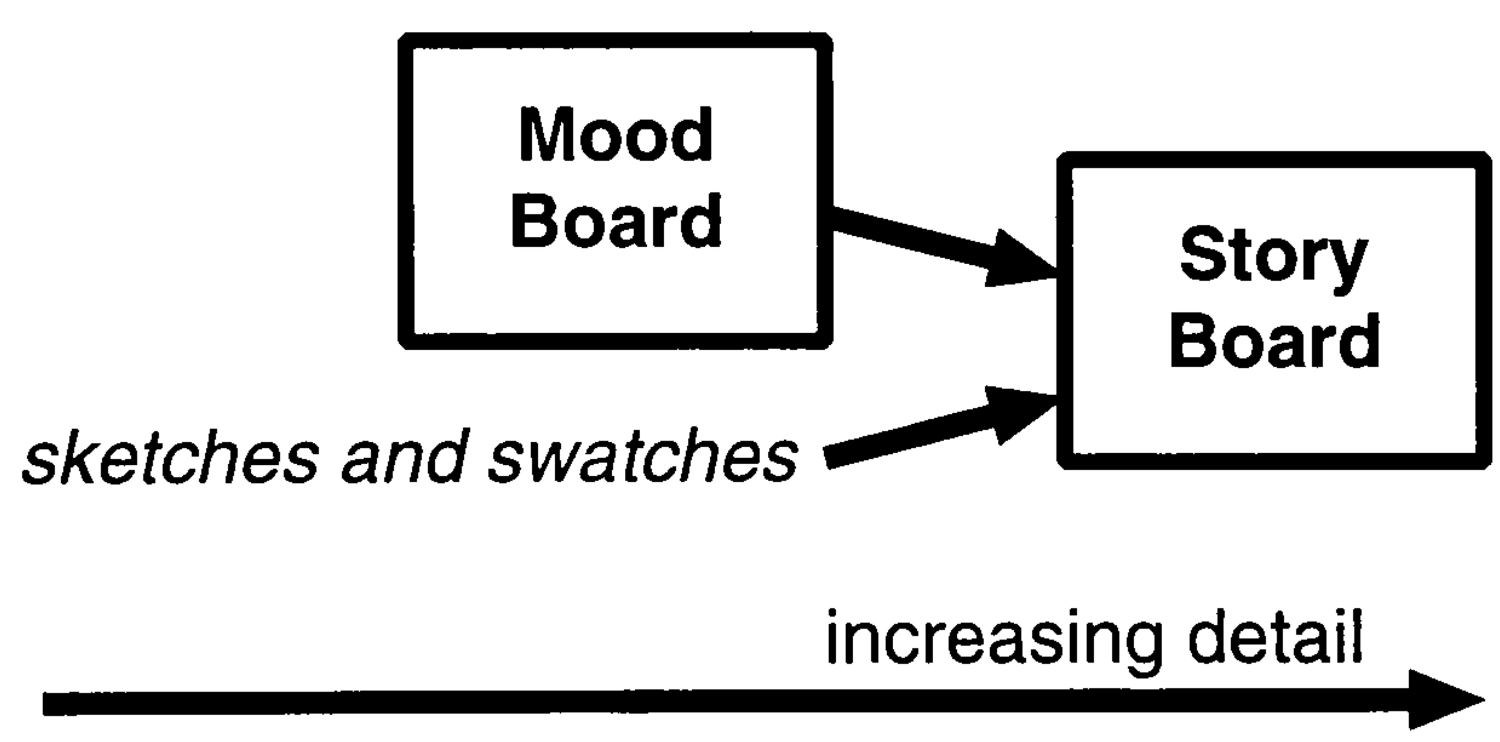
† What is in the shops now has influence because "hanger appeal" is important — e.g. the customer may buy garments to match their coats or shirts.

groups, palette colours are not grouped into *stories* as these are not appropriate to lingerie.

A product is sold by creating a story around it. The creation of story boards is actually a preamble to merchandising and these show where a product fits into the whole theme. A story is explicit in a client's design presentation but not when the item is sold in the stores. Each collection will have a title, a theme and a mood. Garments are often categorised according to the intended customer.

At the same time as producing the story board, initial sketches are started. The ratio of sketches to final products can be as high as 50:1 although their numbers are reduced before they are shown to the buyer. Swatches of the fabric to be used are always shown with the sketches in order to show the scale of the print. From the designs and fabric swatches, a number are chosen to be made into garments. A further selection process then decides which will eventually be put into production. Part of the design process is illustrated in Figure F-1. After receiving approval for designs, extra design work (development) is carried out with the aim of attracting further business. Unlike the core work, only small quantities and a quicker response time (measured in months) are involved.

Figure F-1: Part of the Design Process



The form and pattern of a design may come from existing designs (e.g. wrapping paper) or from sketches. Using their system, consisting of a CAD workstation, flat-bed scanner and ink jet printer, they are able to print directly onto paper, acetate or certain fabrics. The ink jet printer has been set up to produce the widest gamut of colours however they have experienced problems of colour change with time (especially when printing onto unproven media). Because of problems with colour fidelity, decisions cannot be made about screen colours. Only scale and balance adjustments can be made with any degree of confidence. Differences in appearance also arise due to dissimilar media. For example, fabric texture is difficult to simulate on paper.

CAD is useful for showing things that do not exist as this saves the cost of developing samples. It is not used much in the actual design process for nightwear but is used more so for lingerie (because of the fine detail). No free-hand design work is done with the system: either existing designs are used or the work is left to the print designers. Colour mixing is not done on the screen; instead a colour book containing printed charts (each sample approximately $0.75cm^2$) from the ink jet is used. For colour matching, a range of colours close to the target colour are printed out for final adjustment. It is felt that CAD is not appropriate to some people's way of working (they feel too constrained). Its main use is for the support of presentations.

The client's palette, once defined, is first sent to the designer's company as a whole. It is then up to designers to make copies of this for their own reference. If the palette was received earlier in the design process, it could be scanned in and colour matched. This would require them to have one palette for each intended output medium. The Pantone system is the only colour standard employed but even this is seldom used as the designers have experienced inconsistencies with the system. Occasionally, they will print off colours for communication to their printers, but this is no more reliable than Pantone. The most successful way for them to communicate colour is via swatches although it is felt that some sort of reliable colour standard would be beneficial.

APPENDIX G: EXAMPLE DIN CALCULATIONS

Forward Mapping

To illustrate the process of converting DIN notation to CIE XYZ, an example of 7.8:3.3:2.7 is used. Thus, $I_T = \lfloor 7.8 \rfloor = 7$ and $R_T = 0.8$. First, we begin by transforming part of the xyY data in table 1 of [DIN80b] using equation (6.31m) to produce XYZ values:

T:S	x	y	A_0	X	Y	Z
6:6	0.5501	0.3747	45.24	45.2293	30.8079	6.1830
7:6	0.5557	0.3447	38.77	42.5632	26.4019	7.6288
8:6	0.5334	0.3141	36.55	42.2681	24.8901	12.0845
9:6	0.5035	0.2875	36.26	43.2443	24.6926	17.9505

Using this table,

$$f[I_T - 1] = f[6] = (45.2293, 30.8079, 6.1830)$$

$$f[I_T] = f[7] = (42.5632, 26.4019, 7.6288)$$

$$f[I_T + 1] = f[8] = (42.2681, 24.8901, 12.0845)$$

$$f[I_T + 2] = f[9] = (43.2443, 24.6926, 17.9505)$$

Applying Lagrange interpolation for 7.8:6:1 (i.e. T:6:1) to get X_6, Y_6 and Z_6:

$$l_0 = R_T(R_T - 1)(R_T - 2)/-6 = -0.032$$

$$l_1 = (R_T + 1)(R_T - 1)(R_T - 2)/2 = 0.216$$

$$l_2 = (R_T + 1)R_T(R_T - 2)/-2 = 0.864$$

$$l_3 = (R_T + 1)R_T(R_T - 1)/6 = -0.048$$

where l_i are the simplified Langrangian polynomials. The interpolated values for X_6, Y_6, Z_6 are then

$$\sum_{i=0}^{3} l_i f[I_T - 1 + i]$$

Hence, $X_6 = 42.1902$, $Y_6 = 25.0368$ and $Z_6 = 11.0293$. Next, we compute X_6', Y_6' and Z_6' as follows, using D65 values for $X_0Y_0Z_0$ of (95.0449, 100, 108.8917) as before:

$$X_6' = X_6/X_0 = 0.4439$$

$$Y_6' = Y_6/Y_0 = 0.2504$$

$$Z_6' = Z_6/Z_0 = 0.1013$$

Then, $x_6' = X_6'/(X_6' + Y_6' + Z_6') = 0.5579$ and $y_6' = Y_6'/(X_6' + Y_6' + Z_6') = 0.3147$. Next, we find (u_6', v_6'):

$$u_6' = 4x_6' \,/\, (-2x_6' + 12y_6' + 3) = 0.3942$$

$$v_6' = 9y_6' \,/\, (-2x_6' + 12y_6' + 3) = 0.5004$$

Then, for S = 3.3, $u_0' = 0.210526$ and $v_0' = 0.473684$,

$$u' = u_0' + (u_6' - u_0')S/6 = 0.3115$$

$$v' = v_0' + (v_6' - v_0')S/6 = 0.4884$$

Hence

$$x' = 9u'/(6u' - 16v' + 12) = 0.4630$$

$$y' = 4v'/(6u' - 16v' + 12) = 0.3227$$

Finally, using D65 $X_0Y_0Z_0 = (95.0449, 100, 108.8917)$,

$$X = X_0(x'/100y') = 1.3637$$

$$Y = Y_0 = 100$$

$$Z = Z_0(1 - x' - y')/(100y') = 0.7231$$

Therefore, y = 1/(X+1+Z) = 0.324 and x = Xy = 0.442. Again, referring to [DIN80b] table 1,

$$T_{lower} = \lfloor T \rfloor = \lfloor 7.8 \rfloor = 7$$

$$T_{upper} = T_{lower} + 1 = 8$$

$$S_{lower} = \lfloor S \rfloor = \lfloor 3.3 \rfloor = 3$$

$$S_{upper} = S_{lower} + 1 = 4$$

These values are then used as bounding points in trilinear interpolation to obtain the target value of A_0.

$$\begin{array}{lll} A[7][3] = 62.36 & & \\ & A[7][3.3] = 59.579 & \\ A[7][4] = 53.09 & & \\ A[8][3] = 60.99 & & A[7.8][3.3] = 58.4052 \\ & A[8][3.3] = 58.113 & \\ A[8][4] = 51.40 & & \end{array}$$

Hence, $A_0 = A[7.8][3.3] = 58.4052$. Putting this value into equation (6.31m) gives Y = 20.42.

Therefore, the target CIE (x, y, Y) coordinates for DIN notation 7.8:3.3:2.7 are (0.442, 0.324, 20.42).

Reverse Mapping

Using the same example, starting with xyY values of (0.442, 0.324, 20.42) and using the same D65 values for x_0 and y_0,

$$h_{xy} = \tan^{-1}\left(\frac{y - y_0}{x - x_0}\right) = \tan^{-1}\left(\frac{0.324 - 0.3292}{0.442 - 0.3128}\right) = 357.7°$$

This puts the point between the following two entries in [DIN80b] table 2:

h_{xy}	T	r_1
357	7.890	0.03092
358	7.762	0.03096

Using linear interpolation on these,

$$T = 7.89 + \frac{(357.7 - 357)(7.762 - 7.89)}{358 - 357} = 7.800$$

$$r_1 = 0.3092 + \frac{(357.7 - 357)(0.03096 - 0.03092)}{358 - 357} = 0.03095$$

Then,

$$x' = 1.0522x / (0.1337x + 0.0816y + 0.9183) = 0.4633$$

$$y' = y \,/\, (0.1337x + 0.0816y + 0.9183) = 0.3228$$

$$u' = 4x' \,/\, (-2x' + 12y' + 3) = 0.3116$$

$$v' = 9y' \,/\, (-2x' + 12y' + 3) = 0.4885$$

Using these values and u_0', v_0' as before:

$$r = \sqrt{(u' - u_0')^2 + (v' - v_0')^2}$$

$$= \sqrt{(0.3116 - 0.210526)^2 + (0.4885 - 0.473684)^2} = \sqrt{0.01044} = 0.1022$$

By definition, $S = r/r_1 = 0.1022/0.03095 = 3.302$. Using these values of T and S, the value of A_0 lies between the following points taken from [DIN80b] table 1:

T:S	**A_0**
7:3	62.36
7:4	53.09
8:3	60.99
8:4	51.40

Again, using trilinear interpolation to find $A_0 = A[7.8][3.302]$

$$\begin{array}{lll} A[7][3] = 62.36 & & \\ & A[7][3.302] = 59.58 & \\ A[7][4] = 53.09 & & \\ & & A[7.8][3.302] = 58.39 \\ A[8][3] = 60.99 & & \\ & A[8][3.302] = 58.09 & \\ A[8][4] = 51.40 & & \end{array}$$

(This is almost identical to the forward mapping example.) Then, using equation (6.311)

$$D = 10 - 6.1723 \log_{10}\left(40.7 \frac{Y}{A_0} + 1\right)$$

$$= 10 - 6.1723 \log_{10}\left(4.07 \times \frac{20.42}{58.39} + 1\right) = 2.699$$

$\therefore$ T:S:D = 7.800 : 3.302 : 2.699 $\approx$ 7.8 : 3.3 : 2.7.