COLOUR MEASUREMENT

AND

COLOUR REPRODUCTION

SYSTEMS

by

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Submitted in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in the Department of Electronic Engineering of the

University of Natal

Durban : 1987

ABSTRACT

Techniques of colour measurement and colour reproduction are important in a wide range of commercial and social activities in most modern economies. Their study thus constitutes one of the major areas of interest to the CIE.

The project described in this thesis began as an outgrowth of studies of new types of light sources and of the colorimetry of colour-TV systems; plus a conviction that modern TV cameras can operate effectively with a wide range of different illuminating spectra.

It was soon evident that two important prerequisites for this research were: an understanding of the processes of human colour vision; and a knowledge of the standard, international, colorimetric terminology of the CIE. These topics are discussed fully in the text.

Also included is a review of modern gas-discharge lamps, their properties, and their applications. Both high-pressure (HID) types and low-pressure (fluorescent-tube) types are considered.

Because of the need to measure the colours of surfaces and their TV reproductions as accurately as possible, various forms of colorimeter were examined, leading to the choice of a spectrophotometer system for this work. The design, construction, and evaluation of an original spetrophotometer system (the UND Spectrophotometer) are described fully in the text.

Finally, attention is given to the operation of a television system under non-standard lighting. Twelve different light sources were evaluated as TV "taking" illuminants, using both subjective and colorimetric methods of assessment. The experimental results tend to confirm that colorimetric methods are unsuited to colour reproduction evaluation, and that subjective methods are more meaningful. A subjective scale of colour reproduction performance was established, and it was found to correlate closely with the CIE general colour rendering index (Ra) for the various test lamps.

The work reported herein predates similar experiments with TV lighting by other workers, and it includes a wider range of light sources. In spite of differences in experimental technique, however, there is broad agreement with their general results.

CANDIDATE'S DECLARATION

I hereby certify that the research work described in this thesis, except where stated to the contrary in the text, is the result of my own unaided efforts and has not been submitted in part or whole to any other university for any degree.

Signed: A N Chalmers

A N CHALMERS

PREFACE

Colour is, for about 95% of the human race, an inescapable, almost overriding, feature of the visual process. Colour coding is used to improve efficiency and safety in commerce and industry. Colour is the central feature in practically every aspect of environmental design, and it is used to effect in product packaging, advertising, and merchandising. There is thus a clear need for methods of colour specification and colour control in a wide range of modern industries.

Instrumental methods of colour measurement have, over the past 25 years, supplanted virtually all visual colorimetry in routine process– and quality-control in commerce and industry. The main reasons for this are the relatively large spreads in data derived from visual measurement, and the greater accuracy and repeatability of properly calibrated instruments.

Over roughly the same period, colour reproduction in photography, printing and television has advanced from the status of a rare and expensive (but highly appealing) curiosity, to the norm in almost every sphere of activity where these image-reproduction media are employed. The growth in popularity of colour in these media has been due, not only to a decrease in relative costs, but also to the ability to provide a pleasing and (usually) accurate representation of the original colours of the objects in the scenes.

The growth and advancement of technology in all these areas has been aided enormously by the existence of the CIE standard colorimetric observer and the CIE systems of colour specification published in its recommendations of 1931, 1960, 1964, and 1976.

This thesis includes an overview, in Chapter 2, of human visual processes, and colour vision in particular, leading on to an examination of the colorimetric recommendations of the CIE. In Chapter 4, consideration is given to instrumental methods of colour measurement in general, and to the author's performance-evaluation of several different colorimeter systems, leading on to the author's own colorimeter design.

Colour reproduction systems have had to cope with an increasing incidence, thanks largely to their lower overall costs, of gas-discharge type light sources, in many situations which would formerly have been lit by filament lamps.

A common property of gas-discharge lamps is the fact that they possess discontinuous spectra, as opposed to the continuous, near-planckian spectra of filament type sources. This can present serious complications for the operator of the colour reproduction system (who would wish to produce pictures that look as "natural" as possible) since the system does not "see" the scene colours in the same way that the human eye does. On-site visual judgment of the scene illumination is therefore seldom of much use.

Chapter 3 of this thesis provides an overview of modern gas-discharge light sources, and then Chapter 5 describes the author's investigations of the performance of a colour television system that was operated with twelve different such sources in order to establish their ranking as scene illuminants for colour television.

It should be noted that this thesis is concerned with the overall response of a television system to different types of light sources, and therefore no consideration has been given to the communication theory of television systems, nor to the electronic design of television circuits. These topics, although important, are peripheral to this investigation, and are adequately dealt with in a number of excellent texts.

As far as colorimetry is concerned, this document employs only the 2-degree standard observer of the CIE-1931 system, since the 2-degree observer is applicable to field sizes between 1 and 4 degrees – and 4 degrees is about the largest size of uniformly-coloured detail occurring in the subjective tests used in this research. (The CIE-1964 10-degree standard observer is normally used only if the field size is greater than 4 degrees.)

The International System of Units (SI) is used throughout this document, and the comma (,) is used as the notation for the decimal.

A N CHALMERS
DURBAN
MARCH 1987

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my supervisor, Prof H L Nattrass, for his constant interest and continuing guidance in this work.

I am indebted to my co-workers, in particular Dr C J Kok and Dr F Hengstberger (CSIR, Pretoria), Dr R E Jacobson and Dr G G Attridge (Polytechnic of Central London), and all my colleagues and students at the University of Natal, for their numerous useful discussions and their practical guidance and assistance. I would particularly like to thank Dr R Turner of the CSIR for permission to make use of the facilities of the Precise Physical Measurements Division (now the National Measuring Standards and Metrology Division).I have also shared much valuable interaction with members of the International Commission on Illumination, the South African National Committee on Illumination, the Institute of Lighting Engineers of South Africa, and the South African Colour Science Association.

I am grateful for the research grants made over the years by the University Research Fund of the University of Natal, the Research Grants Division of the CSIR, the British Council, and the Mobil Refining Company (Pty) Ltd.

I would like to thank Angela Tucker for typing this manuscript, and Mr P Facoline for preparing the diagrams.

I am also indebted to my colleagues in the workshops of the School of Electrical and Electronic Engineering for their willing and able assistance at all times.

Finally, I would like to thank all my family, and particularly my wife, Diana, for their constant forbearance, encouragement and support in the execution of my research.

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CHAPTER 1

PROLOGUE

1.1 HISTORICAL OVERVIEW OF THE PROJECT

This writer's interest in colour reproduction and colour measurement was initially aroused during the early 1970's with the (then) impending advent of colour television in South Africa [1].

At about the same time there was in the illumination fraternity, considerable interest in the new high-efficacy gas-discharge light sources (or HID lamps) – particularly the High-Pressure-Sodium and Metal-Halide types. There was also, in this writer's opinion, a widespread misapplication of colour photography (colour slides in particular) to "demonstrate" to large audiences the properties of, and effects produced by, these lamps.

This led to a series of photographic experiments [2] with a variety of different light sources, the object of which was to determine the validity of using colour photography for this type of demonstration. It was shown quite conclusively that it was possible to obtain a very wide range of differing responses from the range of colour reversal films obtainable at that time. It was shown, moreover, that the films' responses can be "doctored" to quite a considerable extent, making use of filtration and/or exposure variation, to produce either more or less favourable results. It was this work, in particular, that could be regarded as the foundation of the present project.

Next followed a five-month spell in the Photographic Sciences Unit at the Polytechnic of Central London where the principle of the Figure-of-Merit approach was developed for the physical assessment of colour reproductions, and was applied in a controlled experiment that was aimed at determining the relative colour fidelity of two different processes of Polaroid "instant" colour photography [3,4].

Back in South Africa, this was followed by a period of nearly two years spent on gathering spectrophotometric data on daylight at Durban in a project run jointly with the CSIR [5,6,7,8,9,10]. The primary purpose of this work was to provide improved data on the daylight spectrum for use by the CIE, but it also provides a useful standard of reference when it comes to the consideration of substitute-daylight illuminants in the context of colour reproduction. These measurements of the Daylight spectrum appear to be receiving a measure of international recognition [11].

More or less concurrently with this Daylight work, progress was also being made [12, 13] on the assessment of the reliability of different colorimeter systems, as described in the next section; and this has subsequently led to the design and construction of the UND (University of Natal, Durban) Spectrophotometric Colorimeter [14].

The development of research laboratories as well as undergraduate teaching facilities in colorimetry [13], linked with further studies of the science of colorimetry [15], were interspersed with much of the above work since it was considered important to be able to reconstruct basic colorimetric experiments and to make proper use of the CIE recommendations on colorimetric systems, including chromaticity coordinates and standard colour spaces.

Finally, in 1980, work commenced on the video recording of coloured test scenes under a wide variety of illuminants, and the subjective appraisal thereof [16]. This has been followed by physical measurements of the reproduced test colours in order to make Figure-of-Merit evaluations of the reproductions [17], and further comparisons of the two techniques [18, 19, 20].

Studies have also been carried out to assist local broadcasters in determining the required illuminance levels for television coverage of sports [21].

Contact has been maintained over a number of years with CIE Technical Committee TC1–11 (formerly Subcommittee SC–3.2) on Illumination for Colour Reproduction. While there has been some recent publication of work carried out by this TC [22] on practical assessments of the performance of various lamps in combination with colour television systems, the author believes that his experimental results predate this work by several years. The more recent committee work has been aimed specifically at testing the Television Illumination Consistency Index [23] and has possibly benefited from greater refinement in the available test equipment; but the experimental results reported in this thesis nevertheless, at the time, constituted a novel addition to the available knowledge in this field.

It has to be borne in mind that television test transmissions were only introduced in South Africa in 1975, and television equipment was both rare and expensive in the early 1970's. For this reason, much of the effort in the early part of this project was focussed on colour photography since it was argued that the colour reproduction system could, in many respects, be treated as a "black box", and the main concern was to produce a technique for defining and characterizing the performance of that "black box" rather than becoming over-concerned with its inner workings. This thesis will, however, concentrate for the most part on problems in, and the experiments with, colour reproduction in television.

Recent findings have convinced the author of the importance of subjective appraisal techniques in the assessment of colour reproduction systems, and lamp colour rendering properties, and he has accordingly become involved in the work of CIE Technical Committee TC1-13 on Colour Appearance Analysis [24].

1.2 ESTABLISHMENT OF A COLORIMETRY LABORATORY

It has been described how colorimetric techniques were to be used to evaluate the performance of a colour reproduction system. This concept led immediately to the necessity of establishing a colorimetry laboratory, adequately equipped with instrumentation of proven reliability and performance, with which to carry out the required colour measurements.

It was clear that, if colour television were to be meaningfully assessed, then the colorimeter used for the task would have to be capable of examining that portion, and only that portion, of the television screen containing the colour of interest.

A tintometer visual colorimeter which the author had adapted, by the addition of an exterior viewing port for the measurement of external self-luminous surfaces, was analysed in order to determine its colorimetric performance [12, 13, 25] by comparison with two other colorimeter systems (located at the CSIR in Pretoria) that were made available to the author - viz. the CSIR mask colorimeter [26] and the CSIR Jarrell-Ash monochromator system. Both of these proved to be measurably more reliable than the Tintometer, with the monochromator system somewhat superior to the mask colorimeter.

Neither the precision nor the accuracy of the visual colorimeter was considered to be acceptable for this work, and so it was not considered further for quantitative use in this project.

Based on this experience, and on operational experience with a Leiss monochromator system (that had been on loan from the CSIR for the duration of the Daylight project) the decision was taken to equip the UND colorimetry laboratory with a flexible monochromator system. This has been built up gradually over several years as funds have been made available.

This system (Figure 1.1) is referred to in this work as the UND Spectrophotometric Colorimeter [14]. Briefly, it comprises the following:

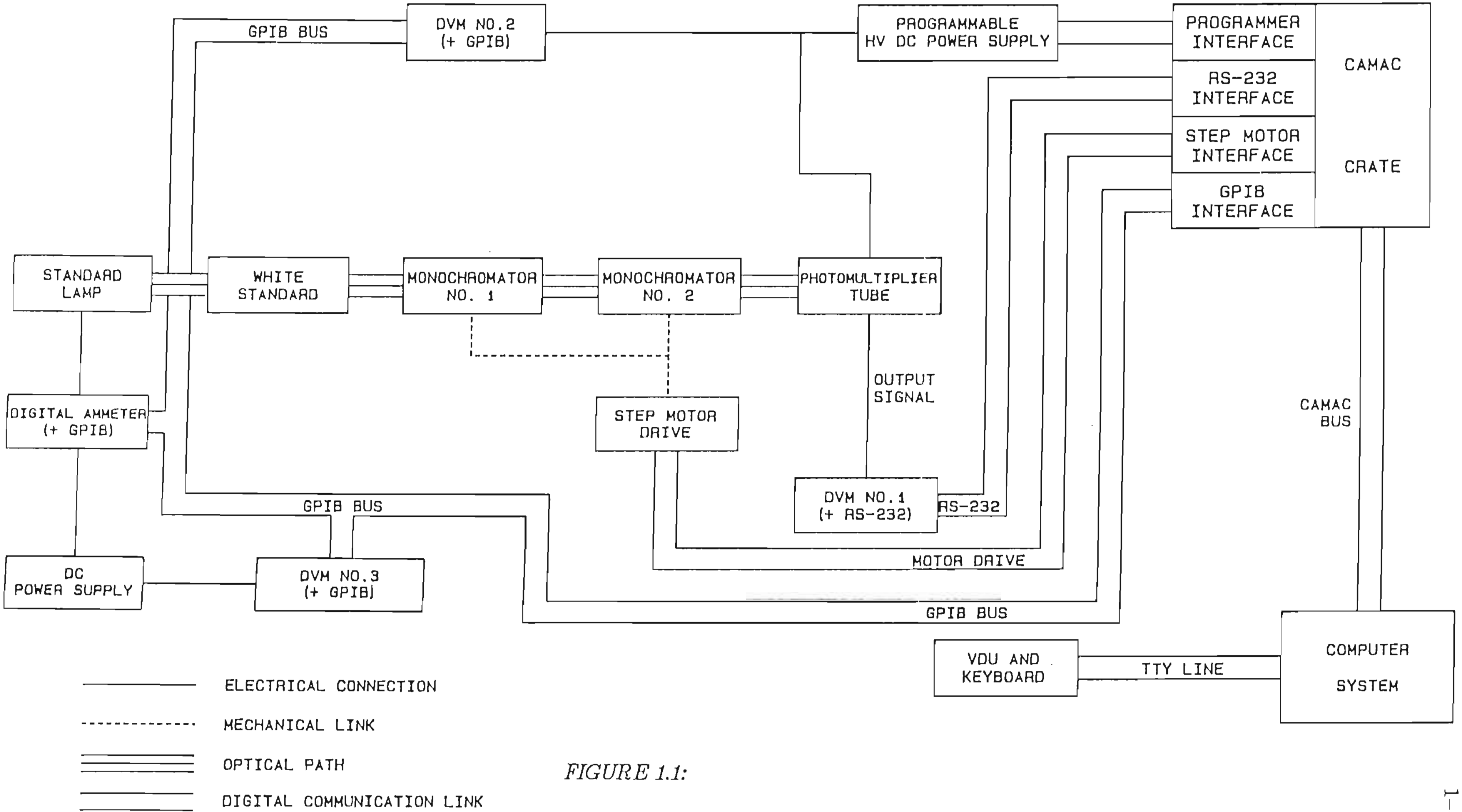

FIGURE 1.1:

THE UND SPECTROPHOTOMETRIC COLORIMETER

(1) Two Jarrell-Ash monochromator units that can be quite simply coupled in tandem to form a double-monochromator unit when required.

(2) Two Thorn-EMI photomultiplier tubes that are mechanically and electrically interchangeable, the one with standard (extended-red S–20) response for measurements over the visible range, and the other having enhanced short-wavelength sensitivity for applications involving UV measurements.

(3) A whiteness standard using pressed Barium Sulphate powder.

(4) A range of tungsten-halogen lamps calibrated as spectral radiance standards.

(5) Associated electronic equipment providing stabilized DC power for the calibrated lamps and for the photomultipliers, monitoring facilities for these power supplies, and a measurement system to read the photomultiplier signal voltage.

(6) Computer interfacing facilities.

The design and evaluation of this spectrophotometer system are covered in depth in Chapter 4.

1.3 AIMS AND SCOPE OF THE PROJECT AND THESIS

The principal aim of the project was to make meaningful experimental assessments of the colour reproduction characteristics of as wide a range as possible of the newer generation of electric light sources. The purpose of this was to classify them in terms of their suitability for use as scene illuminants for colour television.

A subsidiary aim was to attempt to correlate physical measures of system performance with subjective methods of assessment – the “system” here being regarded as the television system in combination with each of the given test lamps in turn.

Physical evaluation of colour reproduction quality was carried out using the Figure-of-Merit approach that had previously been developed in the colour photography experiment described earlier. Subjective evaluation was carried out making use of two scenes that were reproduced under the various test sources, rating the one scene on an impairment (or consistency) scale, and the other on a preference (or quality) scale.

It was soon realized that certain of the abovementioned aims could be met only through the use of a spectrophotometer system of acceptable performance. This would serve as a colorimeter for the purpose of measuring the Figure-of-Merit of the test system, and it could also provide useful information on the spectrum of each of the test lamps. It thus became a further aim of the project to design, construct and test a spectrophotometer system that could meet these needs and that could also be adapted to serve other purposes, should the need arise.

Because a large part of the project was concerned with the measurement of colour and of colour-difference, it was clearly also necessary to become fully conversant with the currently-accepted international standards and terminology in colorimetry. This led to a study of human colour vision and the psychophysical methods of measuring, specifying and quantifying human visual responses – in particular "colour".

It is the author's belief that the remainder of this thesis will demonstrate that the major aims of the project have all been met; and in formulating this document, the author has attempted to introduce the subject matter in what seems to be a logical sequence for the reader. Succeeding chapters will therefore give close attention to the subject matter in the the following order.

Chapter 2 (Colour Vision and Colorimetry) and Chapter 3 (Gas Discharge Lamps in Colour Reproduction) serve to introduce the available knowledge and standard terminology in these subject areas. Chapter 4 (Colour Measurement Systems and the UND Spectrophotometer) considers colorimetric instrumentation in general, and then goes on to describe the design, construction and testing of the spectrophotometer system developed by the author as part of this project. Chapter 5 (Experimental Evaluation of Light Sources for Television Colour Reproduction) outlines two methods developed and employed by the author for the classification of electric lamps in terms of their suitability for television lighting. Chapter 6 (Epilogue) constitutes a closing statement and a summary of the objectives achieved in this work.

1.4 OUTLINE OF PERSONAL CONTRIBUTION TO THE WORK

The claims of the thesis are set out in some detail in Section 6.3, but it may be helpful to consider them briefly at this point.

As will be seen in Chapter 4, a novel, low-cost spectrophotometer system has been produced, with a flexible configuration easily adapted to new forms of measurement that go well beyond the immediate needs of the project. A method has been developed for the assessment of the performance of colorimeter systems generally, and has been applied here to verify the performance of the UND spectrophotometer.

Chapter 5 will show that a method employing the subjective assessment of television pictures has been successfully applied to the evaluation of different light sources for use as television "taking" illuminants (i.e. in illuminating the scene for the cameras). Many (unconventional) HID and fluorescent lamps appear – in the light of this work – to be quite satisfactory alternatives to the tungsten-halogen lamp for both studios and outside-broadcast venues. This finding is clearly of considerable economic significance.

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CHAPTER 2

COLOUR, COLOUR VISION AND COLORIMETRY

This chapter is intended to serve primarily as an introduction to these topics, and it is based largely on three papers given by the author [1,2,3].

2.1 DEFINITIONS OF COLOUR

Probably the most precise and most general definition of colour is that it is a sensation generated within the visual system of an observer, in response to stimuli received in the observer's eye, in the form of electromagnetic radiation within the visible range of wavelengths.

It has been traditional, within the physical sciences, to link specific wavelengths with specific perceived hues; but it is now widely recognized that this approach is limited in application since it ignores the psychosensorial factors that contribute to the perception of colour under different circumstances. These factors give rise to what is often referred to as "subjective colour". Two types of subjective colour are most readily discerned by most observers. These are "simultaneous contrast" and "colour induction".

Simultaneous contrast is the effect observed when a single coloured sample appears to take on two (or more) different colours when it is viewed against two (or more) differently coloured surrounds [4].

Colour induction occurs when a pattern that is comprised predominantly of Colour 1 (say) takes on something of the character of Colour 2, when Colour 2 is included in the pattern [5]. This occurs even though the two different elements are large enough to be separately resolved by the observer. These effects can further be extended to patterns containing three or more different colours, and are used to good effect in carpet and textile design.

A third form of subjective colour is sometimes observed to emanate from purely "black and white" objects when the light entering the observer's eye follows a certain shape of waveform in the time domain (i.e amplitude versus time). This explains the colour sensations observed in the case of the Benham Disc [6] which are discussed further in Section 2.2.2.

The following are some further definitions of colour from specific points of view.

2.1.1 Philosophical

Colour is an attribute conferred on a physical object by virtue of its visual appearance to a human observer [7].

2.1.2 Psychological

The visual appearance of any given object will be determined not only by the characteristics of the light emitted by it, but also by the colour and brightness of the surroundings, and by the state of adaptation of the observer.

Particularly important from the point of view of colour perception, is the matter of chromatic adaptation. This refers to the ability of a human observer to adjust his perception of colour according to the colour characteristics of the ambient illumination [8]. This "colour interpretation" is carried out automatically and is linked to the principle of colour constancy which states that human observers generally see the colour of a given object as invariant under different conditions of viewing and illumination, even though that colour will have been altered physically by the changed conditions [9].

2.1.3 Physical

Physical definitions of colour are based on purely physical measurements such as the measurement of a spectrum [10]. Physical expressions of colour require three "components" to be specified. These are usually as follows:

(a).Dominant wavelength (a hue definition).
(b).Excitation purity (a measure of saturation – the extent to which the dominant wavelength is undiluted).
(c).Lightness (sometimes replaced by the psychophysical quantity, luminance).

2.1.4 Psychophysical

This is the definition of a colour based on a colour match where one compares the "unknown" colour with a colour mixture into which measurable amounts of specific primary colours have been introduced [11]. In most real situations the colour is quantified by correlating its spectrum with the three colour matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ [12,13] defined by the CIE for a 2–degree field (1931) and a 10–degree field (1964). The correlation integrals are three numbers X,Y,Z known as the Tristimulus Values for the particular colour, and they are used in the calculation of numerical colour specifications such as (x,y), (u',v'), etc. (See sections 2.3.6 to 2.3.9).

The term psychophysical indicates that the system is based on human psychological factors (embodied in the colour matching functions) while the necessary measurements are of a purely physical nature.

Ordinary photometric quantities (e.g. Luminous flux, Luminous intensity, Luminance, Illuminance, etc.) are also psychophysical in the sense that they are all based on the measurement of luminous quantities using the V_λ visual weighting function.

For convenience the CIE has chosen to make the $\bar{y}_\lambda$ colour matching function identical to the V_λ visibility function.

2.1.5 Physiological

It is conceivable that physiological definitions of colour could be formulated on the basis of the structure of the human eye and the extent to which the different elements of the eye or visual cortex were to be excited by a given colour stimulus [14].

These have not, to the best of the author's knowledge, been attempted on account of the difficulty of carrying out the required measurements on a living human subject. It is probable, however, that the accepted psychophysical systems are a reasonable emulation of such an approach.

It has been established that the light-receptors in the human retina are of two major types: rods used in scotopic vision, and cones used in photopic vision, and there is strong evidence that cones are of three varieties (red-sensitive, green-sensitive and blue-sensitive).

More recent work has gone a long way toward establishing an Opponent-Colours process within the human retina – a theory that is strongly supported by psychological experiments in colour – and it seems likely that there is some pre-processing (and encoding) of colour information before passing it on to the brain where it is received, recorded and interpreted [15].

This pre-processsing probably leads to the generation of Red-versus-Green, Yellow-versus-Blue, and Black-versus-White information in separate information channels. A psycho-physiological definition of colour could therefore comprise estimates of the amounts of Redness, Yellowness and Whiteness present in the colour.

2.1.6 Psychometric

Various attempts over the years to construct meaningful systems for the quantification of colour have resulted in the conclusion that colour can usually be regarded as a three-dimensional quantity, in the sense that three independent variables are (in most cases) necessary and sufficient for an unambiguous colour specification. (In some large-field situations, where rods as well as cones are the mediating receptors, a four-dimensional specification may be more precise).

The following are a few examples of suitable three-dimensional sets of variables:

(a).Hue, Brightness, Saturation.
(b).Hue, Value, Chroma.
(c).Redness, Greenness, Blueness.
(d).Redness, Yellowness, Lightness.
Etc.

Attempts have been made, with varying degrees of success, to develop systems of colour specification in which the numerical values attached to the coordinates in the various systems are proportional to the perceived sensations which they seek to describe. In other words, one of the aims of a psychometric method of colour specification is a system that possesses a uniform scale of colour difference, irrespective of the colours concerned [16, 17].

The CIE 1976 ($L^* a^* b^*$) and ($L^* u^* v^*$) coordinate systems (see Section 2.3.9) represent attempts to derive psychometric colour scales from psychophysical data [18].

2.2 HUMAN VISION

In terms of its essential elements, the human visual system comprises two eyes, each equipped with a light-sensitive retina, two optic nerves, and two sets of decoding or interpretive centres in the brain, chiefly the lateral geniculate nuclei [19, 20].

The optic nerves from the two eyes meet at the optic chiasma where a crossing-over occurs of approximately half of the nerve-signal-channels (the so-called axons) from each of the eyes. This arrangement ensures that each half of the visual field will be "projected" to the contralateral side of the brain – i.e. the right half of the visual field is decoded and interpreted in the left half of the brain, and the left half of the field on the right side of the brain.

This section contains a brief summary of the major characteristics of human vision.

(i)*Visual Acuity*: The ability to perceive detail (usually about 1 minute of arc under good conditions).

(ii)*Accommodation*: The ability to focus onto objects at various distances, achieved by means of a change of shape of the lens.

(iii) *Adaptation*: The ability of the eye to adjust its sensitivity according to different ambient light levels and spectra. The recovery of sensitive receptors after exposure to high levels of lighting is slow (about 1/2 hour), but adaptation to bright light is very rapid (about a second or less). Adjustment of the iris assists here, but it is by no means the most significant factor.

(iv)*Colour (Chromatic) Adaptation*: The ability to adjust one's perception of colour in a given environment, in accordance with the colour of the predominant light source.

(v)*Binocular Effects*: The duplication of visual responses in both eyes, assisting with the perception of depth and distance (up to about 30 metres).

(vi)*Integration*: The eye can, in general, be regarded as an averaging receptor (i.e. when the stimulus is too fine or too rapid for the eye to produce a precise response, its response will correspond to the "average" stimulus). This applies to patterns both of lightness and colour, as well as to the brightness of intermittent (flickering) light sources.

(vii)*Phototropism*: The viewer's attention tends to be drawn naturally towards the brightest area within his field of view.

2.2.1 The Human Eye:

The principal components of the human eye are:

(i).The Cornea.
(ii).The Iris.
(iii).The Lens.
(iv).The Retina.

(i)*The Cornea:*

Light entering the eye passes first through the cornea which is a tough transparent membrane covering the nearly-spherical protuberance at the front of the eye, and extending over approximately one-sixth of the surface of the eye-ball.

A considerable amount of refraction takes place as the light passes into the cornea which thus acts, in effect, as the first and most powerful lens in the optical system.

(ii)*The Iris:*

The iris is an opaque, fibrous structure, whose central aperture forms the *pupil* of the eye. Two involuntary muscles control the contraction and dilation of the pupil. The pupil diameter can vary between approximately two and eight milimetres, thereby controlling the retinal illuminance – higher values of which tend to produce a smaller pupil diameter.

When the pupil is constricted, the eye's depth of focus is increased. As a consequence, the eye is able to take advantage of higher light levels by improving its optics to enhance visual acuity. Conversely, in dim light, it can trade acuity for increased sensitivity, with larger pupil diameters.

(iii)*The Lens:*

The cornea (as already noted) makes the major contribution to the eye's image-forming ability – due to its high curvature and the fact that its front surface, which is normally in contact with the air, is the only interface where an appreciable change of refractive index occurs.

However, *accommodation* – which is the ability of the eye to focus on objects at different distances – is due entirely to the elastic nature of the lens, and the fact that its shape can be altered through the action of the *ciliary* muscles to provide fine focusing adjustments.

(iv)*The Retina:*

The image of the visual field is formed upon the retina – the screen of light-sensitive nerve-endings at the back of the eyeball.

The retina consists of three main neural layers. The light-receptor elements form the outermost layer. They lie adjacent to the choroid at the back of the eyeball, and their light-sensitive outer segments point away from the lens.

The next layer is made up principally of bipolar cells which provide the interconnections to the ganglion cells. These, in turn, form the innermost layer, and their axons (or nerve fibres) pass over the inner surface of the retina to converge at the optic disc (the so-called blind spot). They all emerge from the back of the eyeball here as the optic nerve. The retina also contains cells which provide lateral connections. The first type are referred to as the horizontal cells. They lie just inside the receptor layer, and link the branches of the bipolar cells over a considerable distance. The second set are the amacrine cells which extend laterally in a layer between the bipolar and the ganglion cells.

The part of the retina which lies about the visual axis is called the *macula* and, for a few degrees around its centre, its structure becomes extremely thin. The chief reason for this is that the axons of the ganglion cells skirt around this region – and the resulting depression is termed the fovea. Two types of visual receptor cells have been identified in the human eye. These are known as the rods and the cones – their names being derived from an approximate description of their shapes.

The rods are responsible for scotopic (i.e "dark adapted") vision and also for peripheral vision (vision "out of the corner of the eye"). They are receptors of brightness and brightness-contrast information and have little or no part in colour vision. They have a very rapid response which helps to make peripheral vision very sensitive to small, quick movements.

The cones are slower than the rods, are incapable of functioning at very low light levels, and function rather poorly at moderate levels of ambient luminance. When the luminance is sufficiently high, they operate very effectively as detectors of colour and fine detail. As with the rods, the cones require time to adapt to any change in ambient lighting.

It is estimated that a single human retina contains approximately 120 million rods and about seven million cones. About 25000 of the cones are situated in the central, rod-free area of the fovea known as the foveola.

The density of the cones falls off rapidly with distance from the foveola, while the density of the rods increases, reaching a maximum at about 20 degrees off the visual axis, and then declining gradually to the edge of the retina.

It seems safe to assume that the central one-degree zone of the retina contains cones only, and that the extent of rod intrusion is negligible within the central two degrees. Most psychophysical studies of colour vision (which is mediated by the cones) have therefore been restricted to stimuli of about this size.

In the foveal region, there is a ratio of approximately 1:1 between the numbers of receptors and ganglion cells – which would seem to be a significant contributory factor to the high visual-acuity of foveal vision.

Since the total number of ganglion cells in a single retina amounts to only about one million altogether, it follows that, in the periphery, there must be a much higher ratio between the numbers of receptors and ganglion cells – of the order of a hundred to one, or greater.

Thus, even allowing for the fact that peripheral vision has poor acuity, and is somewhat deficient in most other respects, there must be a considerable amount of data compression in the retinal layers before the signals are passed to the brain along the optic nerve.

The photo-sensitivity of the rods and cones appears to be related to the bleaching of certain organic pigments in these cells. This fact seems to be well established in the case of the rods, but the evidence in respect of the cones is less certain at the present time although confirmatory views are accumulating as work progresses [22].

The rods contain a crimson-coloured pigment called rhodopsin which has an absorption peak for light at a wavelength of about 500 nm. The visual process in a rod is initiated by the absorption of a single quantum of light energy by one rhodopsin molecule. The molecule then changes its structure, and bleaching is said to have occurred. In some way, this bleaching process gives rise to the transmission of a nerve impulse signifying the fact that light is perceived. In normal circumstances, the bleached pigment gradually returns to its original state, and is said to be regenerated. The rate of regeneration seems to be linked to the state of adaptation of the eye.

Now, it is thought that similar processes take place in the cones, except that different organic pigments will be involved. Recent evidence suggests that there are three cone types, containing different visual pigments with different absorption spectra.

The absorption peaks apparently occur in regions of the spectrum which can be identified roughly as bluish, greenish, and reddish. Thus it is suggested that the human retina contains Blue–, Green–, and Red-sensitive cones. This evidence seems to provide a direct answer to the question of how we perceive colour, which has vexed psychologists and physiologists ever since Newton first discovered the physical basis for colour in the 17th Century.

The colours corresponding to the peaks of the sensitivity curves are not, however, what we might describe subjectively as pure colours [23,24]. In fact, there are good reasons to be found within the realm of experimental psychology for thinking that there are four "subjective primaries" (or unitary hues) viz. Blue, Green, Yellow and Red – and that they are arranged in mutually antagonistic pairs: Blue-versus-Yellow, and Green-versus-Red. This view was first put forward by the psychologist Hering in 1878. The biochemical and physiological details of Hering's theory have not stood up in the light of later findings, though the logic remains sound from the point of view of the experimental psychologist [25].

Also, during the last century, Young and Helmholtz were responsible for an alternative theory of colour vision, which accepted the existence in the human retina of three cone types having distinct spectral sensitivities. In contrast to Hering's approach, however, they proposed only three subjective primaries, Red, Green and Blue, which are the necessary and sufficient components from which white light may be synthesized [26]. The physical side of their argument is irrefutable, and lends itself readily to the explanation of colour mixture effects such as those employed in colour reproduction systems. The weakness of their argument, however, was their proposition that there would have to be red–, green–, and blue-information channels connecting the retina to the brain.

Contrary to this argument, all the evidence now available points to an opponent-colours process being set up somewhere within the network of nerve cells in the retina; and it is now widely accepted that these processes do indeed exist in the human eye. Hurvich and Jameson in the United States of America, and Walraven in Holland, have brought the opponent-processes theory up to date with much additional evidence [27].

Figure 2.1 is a schematic diagram that illustrates a simple model of the way in which the three-colour response of the cones may be converted to the opponent-process signals which are transmitted to the brain.

2.2.2 Subjective Colour Perception

Colour is the psychosensorial correlate of the physical characteristics of the electromagnetic radiation which is entering the subject's eyes. The significant physical characteristics in this context are: the spectral power distribution, as well as the absolute power or intensity, of the incoming radiation. However, the colour appearance of any given object will be influenced by many other factors, the chief of which include the following:

(i).Luminance Level,
(ii).Field Size,
(iii).Surround Luminance,
(iv).Surround Colour, and
(v).Dynamic Effects in Vision.

The following paragraphs will briefly consider the influence of each of these factors. The interested observer with sufficient equipment (and patience) should be able to demonstrate the majority of these effects to himself. They are also capably summarized by Boynton [28].

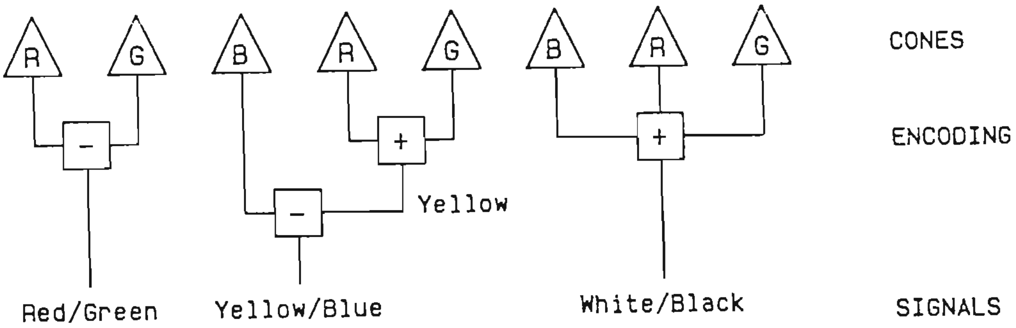

FIGURE 2.1:
SCHEMATIC REPRESENTATION OF POSSIBLE CONVERSION PROCESSES IN RETINA FROM R-G-B TO OPPONENT-COLOUR SIGNALS

The three primary responses of the cones could be operated on in this way to generate three opponent-process signals.

(i)*Luminance Level:*

At very low levels of luminance, there will be no perception of colour since the rod receptors are insensitive to colour, and the cone receptors will be inoperative at these levels.

The cones will come into operation as the luminance is raised, and colours start to become apparent. Further increases in luminance will cause larger signals to be generated; and so, stronger colour-difference signals will be sent to the brain.

This helps to explain the fact the the degree of "colourfulness" in any scene tends to increase as the luminances in the scene are raised.

(ii)*Field Size:*

In very small fields (i.e. less than about 20 minutes subtense) humans tend to become blue-blind, probably due to the near-absence of blue-sensitive cones in the foveola. On the other hand, in fields of more than four degrees, the retinal image tends to "overflow" the fovea, and starts to impinge on rods as well as cones. Small, but noticeable, colour-changes can be brought about by changing the field size from (say) one degree to ten degrees.

(iii)*Surround Luminance:*

For a given set of object colours; darkening their surround will increase their apparent brightness while at the same time it makes them appear relatively less colourful (or less saturated). This is undoubtedly due to the stimulation of receptors surrounding the fixation point, feeding information across to the fovea, most probably through the horizontal cells and the amacrine cells in the retinal nerve network.

(iv)*Surround Colour:*

In a similar sort of way, changing the colour of the surround behind a given set of object colours can change their colour appearance quite dramatically. This is known as the simultaneous contrast effect, and it appears also to be a consequence of the cross-connections existing in the retina, feeding colour-difference information to adjacent colour channels.

(v)*Dynamic Effects in Vision:*

It is not difficult to demonstrate that the human visual mechanism possesses built-in time-constants which render it incapable of responding instantaneously to any sudden change in the incoming light level. For example, it takes an observer about a tenth of a second to perceive that a flash of light has entered his eye. Likewise, the perception of light persists at the same level for a short time after the stimulus has ceased. This is known as the persistence of vision, and is made use of in both television and the cinema, where a series of still images is reproduced in such rapid succession that the observer sees only what appears to be a continuously moving picture.

Coming now to the question of the Benham Disc (Figure 2.2) it can be shown that this black and white device is capable of evoking colour sensations when rotated at a suitable speed; and it seems probable that the subjectively induced hues can be related to the luminance-versus-time waveforms produced within each ring of the disc. One very plausible explanation for these effects suggests that colour information is signalled along the optic nerve to the brain in the form of some kind of pulse code modulation. Thus when observing the Benham Disc in motion, the luminance difference between the white and black sectors of the disc is so great that – even though the Light-versus-Time information is signaled along the Black-versus-White channel of the optic nerve – some of the pulses received at the brain are of the right shape to induce the observed colour sensations [6]. Probably, only small fractions of these signals would reach the colour decoding centres of the brain through crosstalk, and this would help to explain why the "ring-colours" of the Benham Disc are so weak and unsaturated in their appearance.

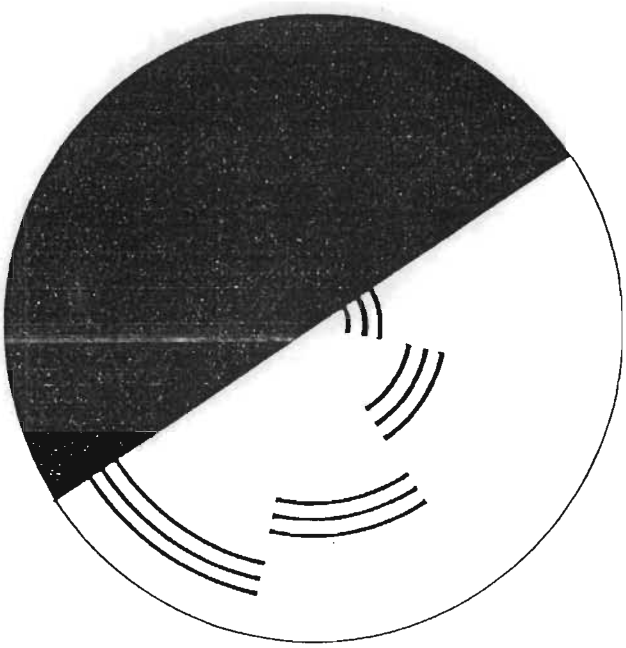

FIGURE 2.2: A BENHAM DISC

When spun at about 1 or 2 revolutions per second, the black-on-white arcs appear to take on different hues (relatively desaturated).

2.2.3 Colour Vision Deficiencies

Among the first workers to have examined defective colour vision in a systematic manner, just about a century ago, were Rayleigh in Britain and Helmholtz in Germany [29].

Over the intervening period, many others have contributed to the expanding body of knowledge on this subject; but it is only within about the last thirty years that physiological explanations for the observed effects have been forthcoming.

It is not intended to give a detailed account of all these factors here, since they are well covered in the available literature [29,30,31]. For the sake of completeness, however, the following brief survey introduces the terminology defining the various forms of colour vision deficiency [29], and their incidence within the population.

The characteristics of persons with defective colour vision may be classified according to their performance in colour matching experiments, in which they are required to match the colour of one light source by a mixture of three primary-coloured sources:

(i).People whose set of colour sensations is three-dimensional can reproduce all colours by a mixture of three fixed colours. These individuals, called *trichromats*, can be divided into the following groups:

(a).normal trichromats or, in short, normal observers;
(b).anomalous trichromats of the first kind, called protanomalous, or red-deficient, observers;
(c).anomalous trichromats of the second kind, called deuteranomalous, or green-deficient, observers;
(d).anomalous trichromats of the third kind, called tritanomalous, or blue-deficient, observers, which are very rare.

Approximately 6% of males and 0,4% of females are anomalous trichromats, with the majority of both sexes suffering from deuteranomaly.

(ii).People whose set of colour sensations is two-dimensional can match all colours by mixing only two fixed colour stimuli. These observers, called *dichromats*, can be divided into the following groups:

(a).dichromats of the first kind, or protanopes, also called red-blind;
(b).dichromats of the second kind, or deuteranopes, also called green-blind;
(c).dichromats of the third kind, or tritanopes, also called blue-blind or violet-blind, which are very rare.

Approximately 2% of males and 0,03% of females are dichromats, with approximately equal incidence of protanopia and deuteranopia.

(iii).People whose set of colour sensations is one-dimensional cannot distinguish any two colours whatsoever; to these any two given colour sensations can be made equal to each other simply by varying the brightness. These observers, called achromats, monochromats or totally colour blind, can be divided into the following groups:

(a).monochromats with blind cones, which are rather rare;
(b).monochromats with colour-blind cones, which are very rare.

Strictly speaking, the much used term "colour blindness" should be applied only to monochromats. Approximately 0,003% of males and 0,002% of females are monochromats.

This classification is based exclusively on the mixing laws holding for the various observers, and therefore on adjustments to equality. Of the other properties of the observers, the colour sensations of the dichromats, for instance, are of particular interest. Does a dichromat, unable to distinguish between certain green and red papers, see them in the same way that a normal observer sees the green paper, or does he get an impression from both papers corresponding to that which the normal observer receives from the red one? This question cannot be solved for people having two dichromatic eyes, for the only means of communicating our subjective sensations of a colour to another person is by means of a description using colour names, and the colour names given by the dichromat are chiefly determined not by his colour sensations but by his obstinate efforts to make his denominations agree with those of the normal observer. Very rare cases have been described in which one eye of an observer is normal and the other dichromatic. In these cases the question can be answered, as the observer can compare the impressions of one eye with those of the other.

All these visual defects are congenital (usually hereditary) and appear to be unalterable during life. There are also far less frequent defects that may arise during life (by injuries, poisoning or disease). These defects are not hereditary and may change in the course of a lifetime, and perhaps even disappear.

In the case of monochromacy of the first and more frequent type, the defect is simply due to the fact that the cones do not function at all and are therefore truly blind. The monochromat of this type can see only with the rods. This fact has a number of consequences which can be predicted directly from the properties of the rods. The most important are the following:

(a).The monochromat is unable to distinguish the various hues. He sees his whole environment in black, grey and white shades. The only difference that he can observe is the difference in brightness. If he is shown any two lights he can make the two sensations indistinguishable simply by varying the luminance of either of the two. His set of "colour sensations" is therefore one-dimensional.

(b).In the central part of his retina (fovea centralis) there is usually a region that cannot give rise to a sensation of light. In order to observe small objects he must always look slightly to one side.

(c).At very low luminance the monochromat sees as well as the normal observer, but at very high luminance he can see practically nothing; he is "light-shy" or photophobic.

(d).His relative sensitivity is that of rod vision.

(e).His visual acuity is very low.

The cones are not entirely absent, but their shape is different from those in normal eyes. Perhaps in some cases they have been partly replaced by rods.

In the second, much rarer type of total colour blindness, the phenomena mentioned under (b) to (e) do not occur. All properties point to the fact that in this case the cones are normally present, maybe even the three photochemical processes are functioning, but by some defect or other the sensations of colour difference do not reach the brain of the observer. At what point a link is missing from the chain of processes is not yet known.

In general, it would be useful for the employer to be aware of any colour vision defects among his employees. For this reason, a variety of different colour-vision tests (e.g. test charts and colour sorting tests) have been devised and produced over the last 100 years or so.

The most serious practical problems are usually found among the dichromats and monochromats. Anomalous trichromats, on the other hand are able to carry out a wide range of colour tasks quite satisfactorily. Their main difficulty is a lack of sensitivity to colour differences, but this is an impediment only in special occupations involving colour judgment or colour control. They also suffer a somewhat reduced ability to recognize signal lights rapidly or under difficult circumstances.

2.3 COLORIMETRY

2.3.1 Additive Colour Mixtures

Thomas Young (in his paper on light and colour in 1802) was the first to show that a mixture of only three independent colours (known as primaries) was necessary and sufficient to synthesize white light [32].

Young projected overlapping spots of light from three sources, providing red, green and blue light respectively, and showed that cyan, magenta and yellow patches are formed where pairs of primaries overlap, and that white can be formed where all three overlap.

In fact, in the region of total overlap, it is possible to produce a very wide range of colours by suitably adjusting the amount of light which is thrown onto the screen by each projector.

The three colours red, green and blue, are described as the additive primaries since all three must be added to produce white light.

An arrangement of the form described, for mixing various quantities of the three primaries to produce a range of new colours, serves as the experimental basis for the measurement and specification of colour.

2.3.2 Metameric and Isomeric Colour Matches

The first step in the quantitative specification of any colour, is that the unknown colour has to be matched in appearance by a suitable mixture of three agreed primaries.

At this point, it has to be noted that the match in appearance may be possible either with or without achieving a complete spectral match. In the relatively rare cases where spectral identity *is* achieved, the match is referred to as an *isomeric* match. In all other cases, where a match in appearance is achieved with non-identical spectra, the match is said to be *metameric* [33].

The reason for metameric matches being possible, is that the eye does not analyse the spectrum; instead it produces an integrated response which is interpreted as a single colour.

It is, incidentally, this fact that enables us to achieve reasonably high degrees of satisfaction with practical colour reproduction systems, such as photography and television. The reproduced colours are, usually, approximately metameric with the original colours in the scene, and virtually never isomeric.

2.3.3 Maxwell's Experiment

The first colour photograph was made by Maxwell in 1861, in an attempt to illustrate the three-colour-basis of human vision [34]. He took three black-and-white photographs of a still scene, one through a red filter, one through a green, and a third through a blue filter. From these, he made three black-and-white positive lantern slides. These were simultaneously projected in register onto a screen from three projectors, in front of each of which were placed the same three filters, in their correct respective positions. To his delight, Maxwell found that he had obtained a full-colour reproduction of the original scene; and his ideas have served as the basis of most modern colour reproduction systems.

It does *not* seem to be very widely realized that the success of Maxwell's experiment depended on a fortuitous anomaly in his system, of which he was, almost certainly, unaware at the time. It is quite certain that no photographic emulsion which would have been available to him could have had any significant red sensitivity; but his red filter apparently possessed quite a significant blue pass-band so that the red component of his projected picture was obtained purely through exposure of the emulsion to blue wavelengths. Fortunately, many real red surfaces also possess quite significant reflectances in the blue region of the spectrum, and so his system actually worked!

2.3.4 The Colour Triangle

Maxwell went on to show that a colour mixture could be represented by a point within an equilateral triangle whose apices R, G, B, represent the three primary colours [35]. In Maxwell's approach, the centroid of this equilateral triangle represents the white (or neutral) point, implying that he required equal amounts of his three primaries to produce white light, since the centroid in this triangle is equidistant from the three apices. He used these distances from the apices also as a measure of the relative amounts of the three primaries required in any other mixture.

2.3.5 The (r,g) Chromaticity Diagram

A more modern adaptation of Maxwell's approach was the (r,g) chromaticity diagram, constructed on a right-angled triangle (Figure 2.3). The three primaries, R, G, and B are again located at the three apices of the triangle. The r and g coordinates are plotted as the proportions of the Red and Green primaries, respectively, required in a Red-Green-Blue mixture, to achieve a match with any other colour [36].

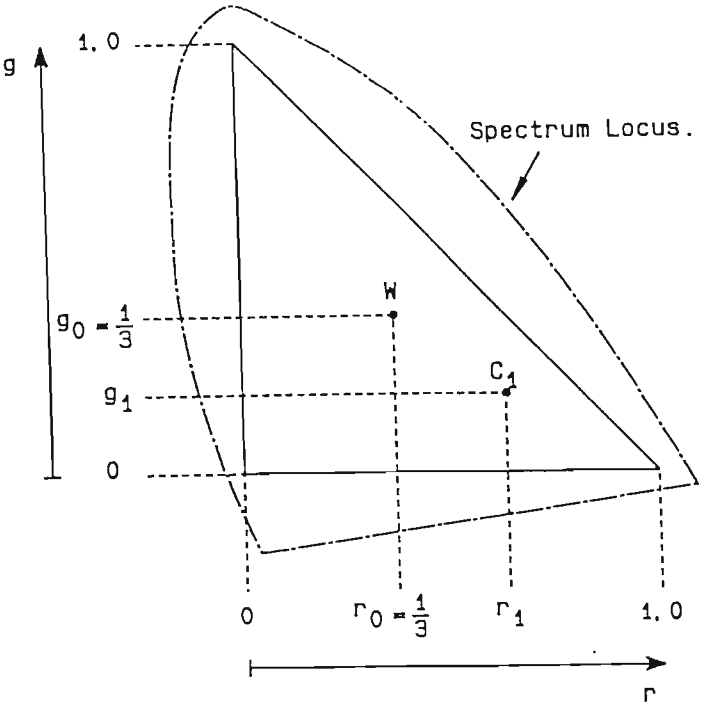

FIGURE 2.3: AN (r,g) CHROMATICITY DIAGRAM

All real colours lie within the spectrum locus.
All additive mixtures of the primaries R,G,B lie within the right triangle.

For example, if R_1, G_1 and B_1 represent the quantities of red, green and blue light required to achieve a colour match with some given test colour, then the point plotted on the triangle will have coordinates r_1 and g_1 determined by the two equations:

$$r_1 = \frac{R_1}{R_1 + G_1 + B_1} \quad \text{and } g_1 = \frac{G_1}{R_1 + G_1 + B_1}.$$

The coordinates r_1 and g_1 are termed the chromaticity coordinates for that particular test colour. Note that the units in which the three primaries, R, G, and B, are measured, are normalized in such a way that unit amounts are required to match white light. The white mixture is thus given by equal quantities $R_o = G_o = B_o$ and hence the chromaticity coordinates of the white point on the chromaticity diagram are $r_o = g_o = 1/3$.

This type of chromaticity diagram was found to suffer from one unfortunate disadvantage which arises from a feature inherent in human vision: namely that, however carefully one selects the three primaries, there is always a certain range of pure spectral colours which cannot be matched by a three-colour mixture of the form described. However, a match can be achieved under these circumstances by a so-called *negative* matching technique – which involves mixing *one* of the three primaries with the unknown (test) colour, diluting it to a certain extent, and then mixing the remaining *two* primaries in an appropriate proportion to obtain a match between the two mixtures.

Typically, the test colour in this kind of situation might be a cyan (or blue-green) coloured light-source. This will be diluted by mixing it with the red-coloured primary source, to obtain a much less intense (or, less saturated) colour, which can then be matched by a simple mixture of the Blue and Green primaries. Suppose that the quantities of the primaries in this situation are R_2, G_2 and B_2, then the chromaticity co-ordinates for the cyan test-colour would be defined by:

$$r_2 = \frac{-R_2}{R_2 + G_2 + B_2} \quad \text{and } g_2 = \frac{G_2}{R_2 + G_2 + B_2}$$

The negative sign attached to the expression for r_2 here is the mathematical way of saying that the red primary had to be taken out of the colour mixture, and effectively "subtracted from it", by physically mixing the red primary with the test colour instead of with the other two primaries.

Using negative matching techniques, it is found that all real colours can be matched by three primaries, but that nearly all of the most highly saturated (spectrum) colours lie outside the basic colour triangle.

2.3.6 The CIE–1931 (x,y) Chromaticity Diagram

The CIE (the International Commission on Illumination) has, since the earliest days of its existence, concerned itself with the questions of measuring and specifying colours – and, in 1931, the CIE recommended a system of colorimetry based on the work of Wright and Guild, which has the important advantage that the chromaticity co-ordinates always remain positive [37–40].

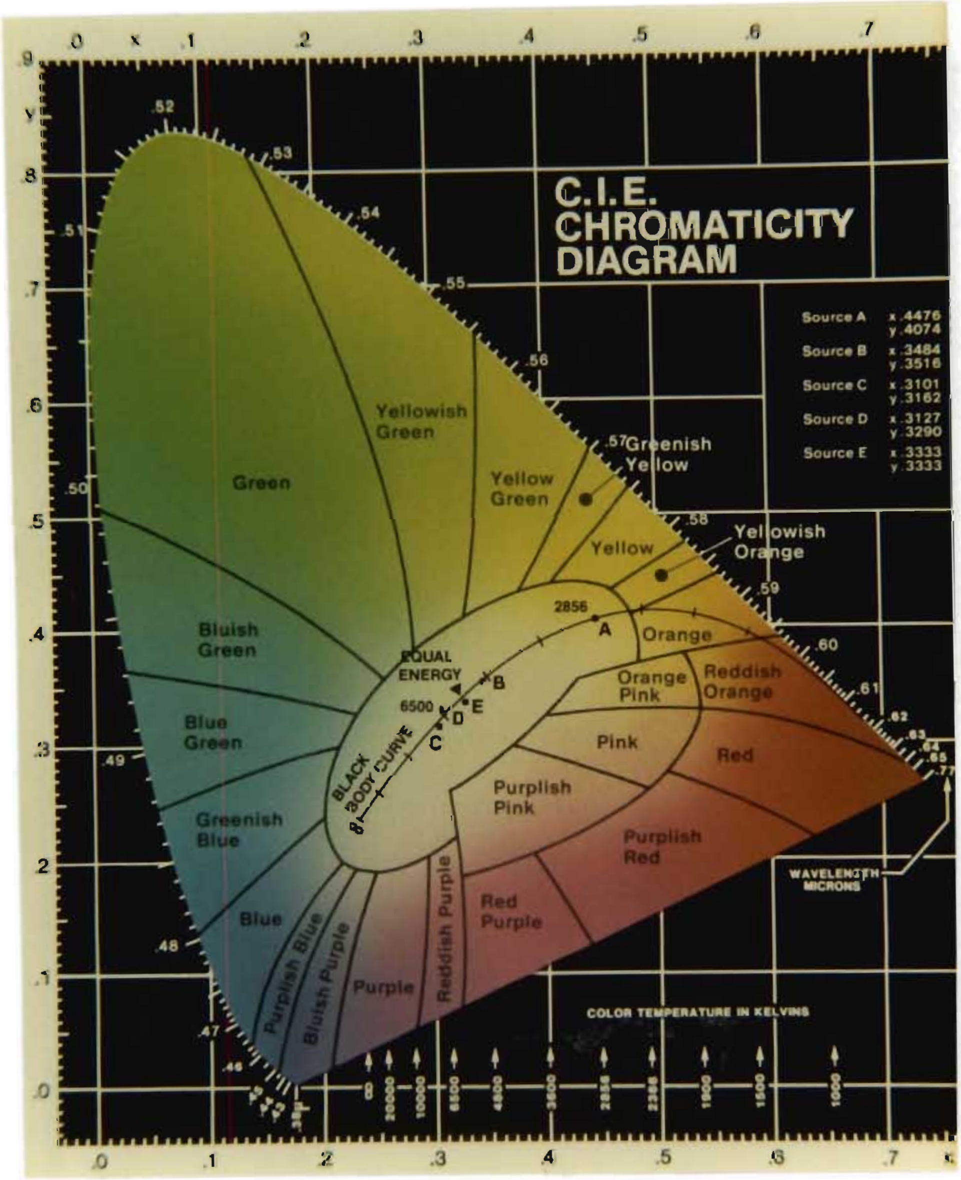

FIGURE 2.4: CIE–1931 (x,y) CHROMATICITY DIAGRAM

Showing the spectrum locus, the full radiator locus, and the chromaticity points of CIE standard illuminants A,B,C,D_{65} and the equal-energy point E.

(Courtesy Photo Research, California, USA)

This can be done only by choosing primaries which are not real colours – a concept which newcomers to the subject often find difficult to accept. However, it becomes easier to understand this idea if it is realized that – although these are purely imaginary as colours – they do exist as real points on the chromaticity diagram.

Colour measurements are, of necessity, made with real primaries, and algebraic transformations are made to convert these measurements to express the data in terms of the unreal primaries.

Using these techniques, the CIE (x,y) chromaticity diagram (Figure 2.4) is obtained as a linear transformation from the earlier (r,g) diagram. In this system, capital X, Y and Z represent the super-saturated (unreal) primary colours, termed Tristimulus Values, and a match with any given test colour is represented by a corresponding point on the chromaticity diagram.

For example, if the test colour is matched by quantities X_1, Y_1, Z_1 of the three primaries, then the chromaticity co-ordinates are given by the following equations:

$$x_1 = \frac{X_1}{X_1 + Y_1 + Z_1} \quad \text{and } y_1 = \frac{Y_1}{X_1 + Y_1 + Z_1}$$

The Tristimulus Values are again normalized so as to yield a white point on the diagram with the co-ordinates:

$$x_o = y_o = 1/3.$$

The fundamental definitions of the three Tristimulus Values are in terms of their spectral weighting functions $\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$, known as the colour matching functions.

Each tristimulus value is then found by integrating the light energy flux emanating from the test source relative to the appropriate colour matching function, as shown in these three equations:

$$X_1 = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{x}_\lambda\, d\lambda$$

$$Y_1 = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{y}_\lambda\, d\lambda$$

$$Z_1 = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{z}_\lambda\, d\lambda$$

(where k is a constant for the set)
from which the chromaticity co-ordinates x_1 and y_1 can be calculated by simple linear algebra, as shown earlier.

Hence it is seen that the fundamental method of determining the chromaticity co-ordinates of a source is to measure its radiant spectrum $\phi_{e\lambda}$, and – usually nowadays – to employ digital computation to carry out the necessary integration and transformation calculations which yield x_1 and y_1. The CIE system was designed using $\bar{y}_\lambda = V_\lambda$, so that the Y tristimulus value can be used as a measure of the relative luminance (or objective brightness) of the unknown colour.

2.3.7 Colour Differences and the MacAdam Ellipses

The visual significance of distances between points on the 1931 (x,y) chromaticity diagram was not considered at the time that the diagram was devised and adopted. However, as soon as it came into use, it quickly became evident that the (x,y) diagram does not represent perceptually equal colour differences by equal distances between points that represent equally luminous colours [41].

Suggestions were made to change the representation of chromaticity in such a way that equal distances would represent equally noticeable colour differences. In MacAdam's words in his recent book [42]:

> "The hoped-for chromaticity diagram with such properties came to be called 'uniform'. The search for it has extended over 50 years and seems no nearer its goal than at the beginning. Much of the accumulated evidence indicates that the goal is unattainable – that a flat diagram cannot represent equal color differences by equal distances any more than a flat map of the world can represent equal geographical distances by equal distances on the map. Nevertheless, useful methods have been devised for evaluating color differences in terms of chromaticity differences."

It is probably true to say that MacAdam himself has been the greatest contributor to the effort over the years to define a Uniform Chromaticity Scale (UCS); and his MacAdam ellipses are probably the most widely used technique available to enable one to attach a visual significance to the magnitudes of the chromaticity-differences measured in different regions of the (x,y) diagram.

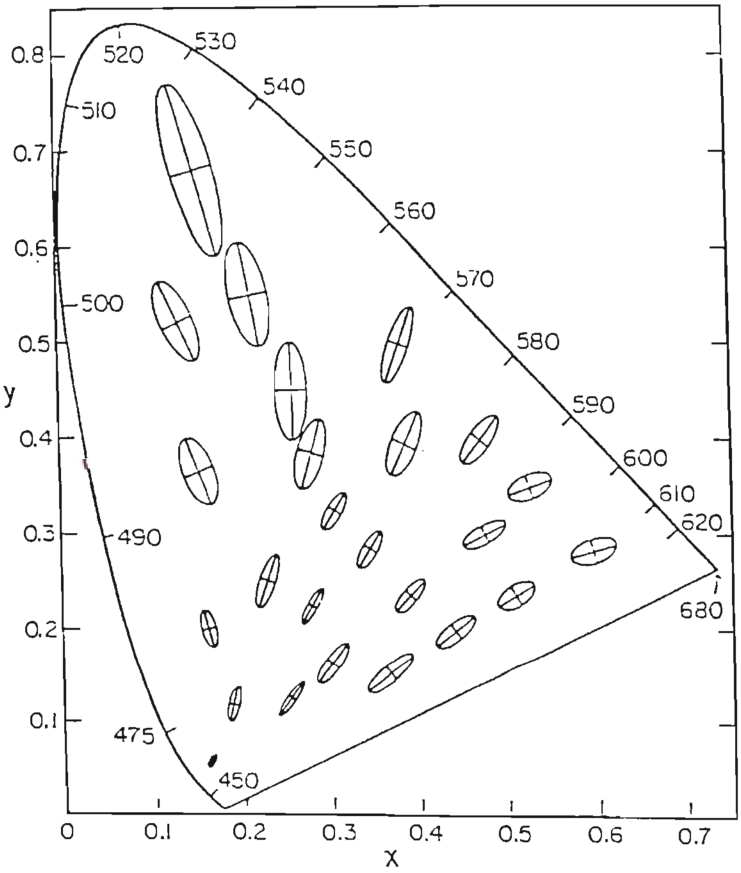

FIGURE 2.5:
MACADAM ELLIPSES IN THE CIE–1931 CHROMATICITY DIAGRAM

Each ellipse represents the same subjective difference in chromaticity.

(Reproduced from MacAdam [43] Fig. 8.3.)

With the aid of a single colour-normal observer, MacAdam undertook a systematic experimental investigation in which colour-matching techniques were used to establish a set of ellipses of equally-noticeable observed colour differences around 25 standard chromaticity points, widely scattered over the area of the (x,y) chromaticity diagram. These ellipses are shown (10 times enlarged) in Figure 2.5 which is a copy of MacAdam's Figure 8.3 [43].

In this Figure, the radius in the direction of variation is *ten times* the standard-deviation of 30 matches in a single observation session. Six to eight directions of variation through each colour centre were used. In a separate experiment using the same observer, it was found that a just-noticeable-difference of chromaticity (sometimes called 1 JND) is about double the standard deviation in the colour matching experiment. Therefore, the radii of the ellipses as they appear in Figure 2.5 represent about 5 JND units.

It is evident that an ideal UCS system would convert the MacAdam ellipses to a series of identical circles, and a large body of workers has contributed to the search for this ideal system over the years since the CIE (x,y) diagram was adopted in 1931.

2.3.8 The CIE–1976 (u',v') Chromaticity Diagram

The CIE has, it would seem, attempted to make pragmatic recommendations for UCS systems which – even though not ideal – are significant improvements on the (x,y) system from the point of view of chromaticity scaling. Thus it was that the CIE adopted the (u,v) chromaticity diagram in 1960, and the improved (u',v') version of this system in 1976 (Figure 2.6).

The differences between the two systems are quite simple, with u' = u and v' = 1,5v. The new chromaticity co-ordinates, u' and v', were defined in such a way that colour differences plotted on this chart are of a more-nearly-equal step-size for colour differences which are judged as being subjectively equal [44].

Although perfect uniformity has not been achieved, the u' and v' co-ordinates have the great advantage of being simple, linear functions of x and y – and so transformations between the two systems can be carried out by the use of two simple equations:

$$u' = \frac{4x}{-2x+12y+3} \quad \text{and} \quad v' = \frac{9y}{-2x+12y+3}$$

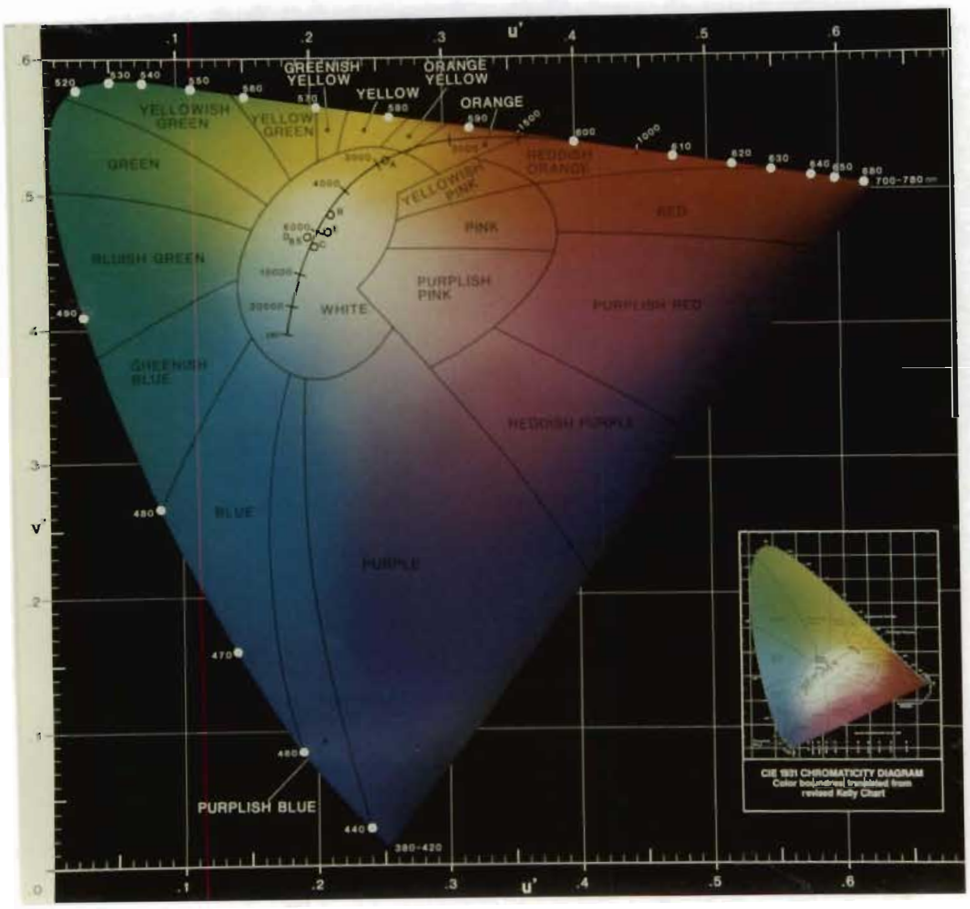

FIGURE 2.6: CIE–1976 (u',v') UCS CHROMATICITY DIAGRAM

Showing the spectrum locus, the full radiator locus, and the chromaticity points of CIE standard illuminants A,B,C,D_{65} and the equal-energy point E.

(Courtesy Photo Research, California, USA)

2.3.9 The CIE–1976 Colour Spaces

In the years since 1960, the CIE Colorimetry Committees have devoted much of their effort to the formulation of quantitative techniques of colour specification which more accurately reflect the subjective appearance of colours and colour-differences [18].

The CIE–1976 ($L^* u^* v^*$) colour system makes use of a three-dimensional colour space which permits the definition of the lightness of a colour as well as its chromatic nature. L^* is the psychometric lightness co-ordinate, and it is defined by the equation:

$$L^* = 116 \left[\frac{Y}{Y_n} \right]^{1/3} - 16$$

where Y_n represents the luminance of the nominally white reference surface.

u^* and v^* are referred to as the CIE–1976 *chroma* co-ordinates, and they are derived from the 1976 u' and v' co-ordinates, taking into account the lightness L^* and the illuminating-source-colour (represented by the co-ordinates u'_n, v'_n):

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

and

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

Planes of constant lightness (normal to the L^* axis) contain a series of chroma diagrams (of u^* versus v^*) whose sizes gradually diminish as the lightness is decreased – finally converging at the black point where:

$$L^* = u^* = v^* = 0.$$

In regions of the space representing "average" lightness conditions, the chroma diagram takes on a form similar to the 1976 (u', v') diagram with the difference that the origin is now shifted to coincide with the white point.

The CIE–1976 ($L^*a^*b^*$) colour space is similar in concept and purpose to the ($L^*u^*v^*$) space, except that it had its origins outside the CIE, and was developed for purposes of industrial colour control, rather than colour specification. The two colour spaces were adopted simultaneously by the CIE and given equal status until some future time at which one may hope for the selection of a single improved system.

The L^* co-ordinate is the same in both systems, but the chroma co-ordinates are defined quite differently. Here:

$$a^* = 200 \left[\left(\frac{X}{X_n} \right)^{1/3} - \left(\frac{Y}{Y_n} \right)^{1/3} \right]$$

and

$$b^* = 500 \left[\left(\frac{Y}{Y_n} \right)^{1/3} - \left(\frac{Z}{Z_n} \right)^{1/3} \right]$$

Here X_n, Y_n, Z_n are the tristimulus values of the nominally white reference surface.

Robertson [16], in attempting to provide data for the evaluation of the relative merits of the two CIE 1976 colour spaces, has replotted MacAdam's ellipses in (a^*, b^*) and (u^*, v^*) chroma diagrams for constant lightness ($L^* = 50$). These are reproduced here in Figure 2.7, and show no evidence of any clear superiority of either system over the other.

It is perhaps interesting to note, in closing, that L^* is a measure of subjective lightness, while a^* and u^* are measures of redness-versus-greenness, and b^* and v^* are measures of yellowness-versus-blueness. These then are systems which not only attempt to correlate with subjective effects in evaluating colour differences, but also appear to give some recognition to fundamental visual phenomena by recognizing the four so-called "unitary" hues of the opponent-processes theory (ie. Red, Yellow, Green, and Blue).

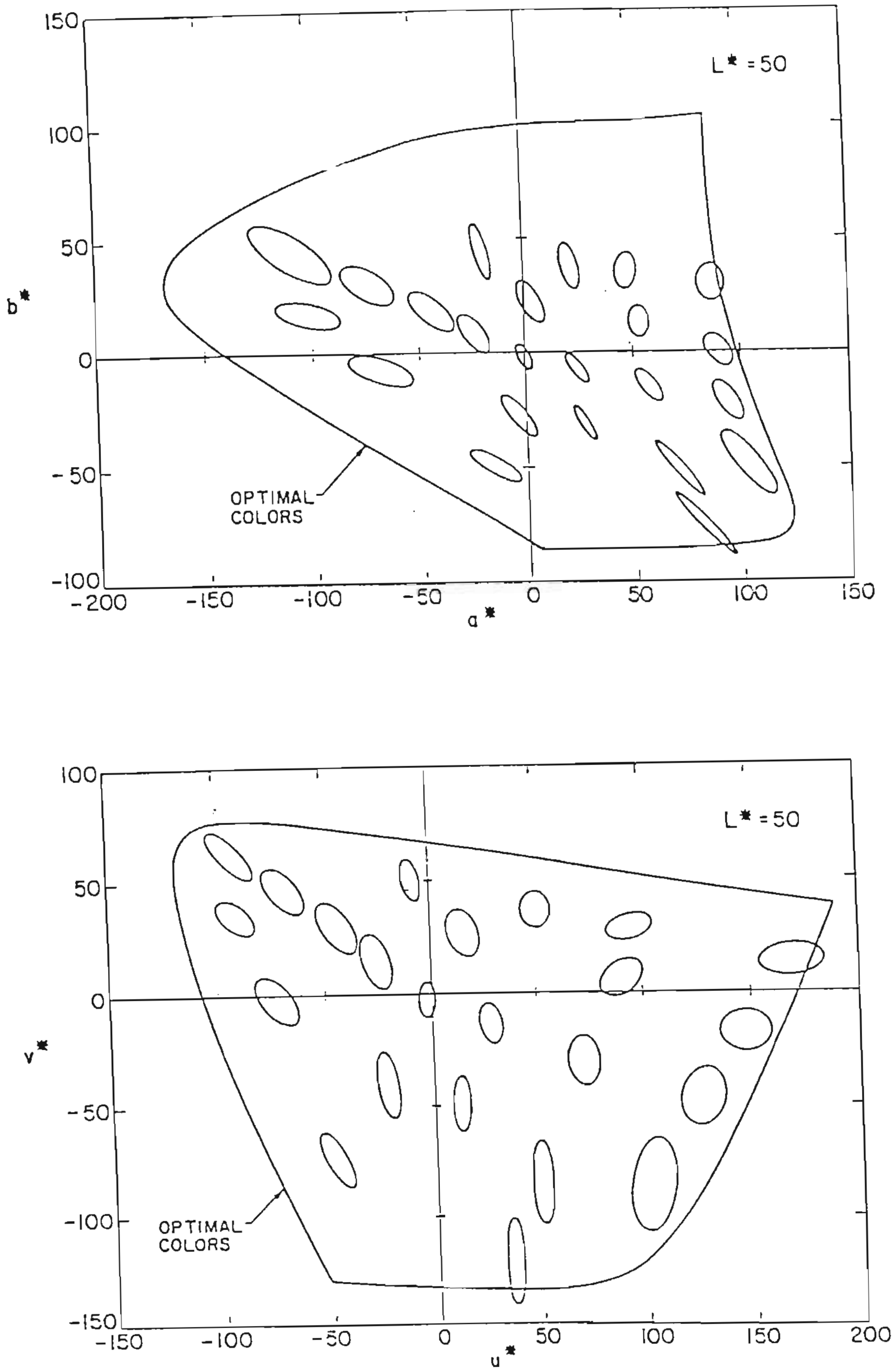

FIGURE 2.7: MACADAM ELLIPSES
REPLOTTED IN CIE–1976 CHROMA COORDINATES FOR $L^* = 50$.

Upper: (a^*, b^*) plot. Lower: (u^*, v^*) plot.

(Reproduced from Robertson [16] Fig. 6.)

2.4 SUMMARY AND CONCLUSIONS

The purpose of this chapter has been to introduce the fundamental ideas and terminology concerning colour, colour vision and colorimetry.

An attempt has been made to introduce some of the philosophy of Colour Science, and to explain this by reference to the current knowledge of the mechanism of human colour vision.

The final section of the chapter has concentrated on systems of colour specification, with particular emphasis on the systems to have been adopted by the CIE, since it is these systems that provide the vocabulary and syntax without which modern colour scientists would be unable to communicate effectively.

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CHAPTER 3

GAS DISCHARGE LAMPS IN COLOUR REPRODUCTION

3.1 INTRODUCTION

General reviews of the CIE approach to this topic have been published in recent years by Taylor [1] and Sproson [2,3] among others.

This chapter serves as an introduction to the modern members of the gas-discharge lamp family, and considers their potential applications as "taking" illuminants in colour reproduction systems. (The term "taking" is used here to signify "picture taking" or "picture-making" as opposed to the "picture-display" or "projection" stage of a colour reproduction process.)

Gas discharge lamps can be broadly classified into two categories:

(i) High Pressure Lamps: These are generally of compact design which, coupled with their high lumen output, leads to these lamps possessing high values of intensity – hence the term HID for "High Intensity Discharge" lamps.

(ii) Low Pressure Lamps: These tend to be of relatively large physical size coupled with relatively low lumen output, and hence relatively low intensity. The low pressure gas discharge is essentially monochromatic in character. In the case of low pressure mercury, the 254 nm resonance line is exploited as the irradiating source (for the phosphors within the tube) in the wide range of tubular fluorescent lamps now available.

3.2 HID LAMPS

In recent years there has been steady development of the HID range of lamps [4]. These are gas discharge lamps of high luminous efficacy and high light output. Being physically small ("point" sources) they possess high intensities.

These lamps were initially developed for exterior lighting applications (such as roadway lighting) where large quantities of light flux are important but colour characteristics are relatively unimportant. One of the developments that has continually taken place with these lamps over the years, however, has been the steady improvement in their colour rendering properties while still retaining very high values of luminous efficacy.

The application of these lamp types has therefore spread to situations where colour rendering is of some importance – such as in flood lighting of goods yards and of sports arenas, and in interior applications in heavy industry, light industry and even interior commercial applications such as warehouses, shopping malls, supermarkets and lately also in offices [5,6,7].

As a consequence of these developments, these lamps have been used as illuminants in situations where colour reproduction systems (specifically colour TV and colour photography) have been applied, and the influence of these sources on the colour quality of the reproduced picture has become technically significant and commercially important [8,9].

3.3 TELEVISION OUTSIDE BROADCASTS

With the growth of commercialism in sport and the increasing coverage of sponsored night-time sports events on the national and international television networks, there has been considerable interest in the methods of providing lighting for these events in such a way as to ensure acceptable viewing conditions for the players and the spectators at the ground, as well as sufficient light of the required colour quality for the purposes of the TV OB (television outside broadcast) units and also for on-the-spot colour photography.

The lighting levels and colour quality criteria are particularly important in the TV application [10,11,12] since it is often the case that a TV network will switch between different OB venues during the course of a programme, and will also cross between OB's and studios, and there is a need to ensure as far as possible that the colour reproduction quality, as sourced from the different venues, at least remains consistent, even if not ideal.

In the early stages of colour television outside broadcasts, it was common to specify only Tungsten-filament or Xenon-discharge lamps as acceptable from the colour rendering and reproduction points of view. Both were very expensive solutions, being relatively inefficient (both yielded around 20 lm/W) and the further disadvantage of the high-power Xenon lamps then in use was that they had to be operated with complex and expensive control gear which tended to be unreliable. Both lamp types had short life.

The Xenon lamps produced a spectrum that was a reasonably close match to daylight at a colour temperature around 6500K and were therefore said to be daylight compatible (i.e. cameras set up for use in daylight could also be used under this source with little or no realignment).

The filament lamps were usually tungsten-halogen lamps which were (and are) also the standard studio lamp. They were therefore said to be studio compatible.

The tendency in recent years has been to phase out the use of these low-efficacy lamps wherever possible, and to replace them with high efficacy (usually HID) lamps having suitable forms of SPD (spectral power distribution).

In the context of colour reproduction, this requirement (for a "suitable" SPD) has conventionally been taken to imply a near-flat spectrum, or at least a spectrum with a multiplicity of closely spaced peaks. While this is a simple rule of thumb to ensure good colour properties, it is almost always going to lead to sources possessing relatively low values of luminous efficacy.

These facts led this author to question the conventional wisdom summarized above, and to set out to establish, by experiment, the relative merits of some of the wide range of lamps now readily available. The relevant television colour reproduction experiments are described in Chapter 5 of this document.

3.4 MODERN HID LAMPS

3.4.1 Metal-Halide Lamps

With the development and practical application of modern HID lamps from about 1970 onwards, TV broadcast authorities and lamp makers began to recommend the use of metal-halide lamps for OB purposes [13]. These lamps have far lower power consumption than ether Xenon or Tungsten-Halogen lamps since their luminous efficacy is typically of the order of 100 lm/W. However, their lamp life is often not much better than that obtainable with Xenon and Tungsten-Halogen and lamp replacement costs tend to be high. On the other hand, capital costs can be lowered since the power supply requirements are reduced by a factor of 4 or 5. It has to be borne in mind that Metal-Halide is a generic name for a whole family of lamps, the chief features of which are that they are essentially mercury-vapour lamps in which additional active constituents have been introduced into the discharge tubes. These active constituents are salts, the most useful of which have been the halide salts of certain metallic (mostly alkali and alkali earth) elements (hence their name).

Many different metal-halide salts have been used by different manufacturers and one has to be aware that they can differ very markedly one from another in spectral power distribution [14–21].

The chief spectral characteristic of these lamps is the existence of very large numbers of closely-spaced lines, yielding a discrete approximation to an equi-energy spectrum. Typical values of R_a (CIE colour rendering index) for practical lamps are 65 and above, and correlated colour temperatures (T_c) lie in the range from about 4000 K to 8000 K.

Problems commonly experienced with these lamps include starting difficulties, unpredictable failures, and random colour shifts through life.

3.4.2 High Pressure Mercury-Vapour Lamps

The Mercury-Vapour lamp was never regarded as a very serious contender for OB applications since its efficacy is noticeably lower than the Metal-Halide lamps', although its life expectancy is often far greater.

A major problem with the "uncorrected" (clear-bulb type) Mercury vapour lamp was the absence of any long-wavelength radiation, making the rendering and reproduction of reds very poor.

The last 20 years or so, however, have seen the development of several different types of phosphor suitable for the "colour correction" of the Mercury-Vapour lamp. These have all operated on the principle of absorbing the invisible UV radiated by the mercury discharge and re-emitting the energy in the long-wavelength (Red) end of the visible spectrum, to make good the deficiency in the mercury spectrum. The phosphor is coated on the inner surface of the lamp's outer bulb, and the coating is so designed as to cause as little attenuation as possible to the visible wavelengths produced by the discharge.

These lamps have been steadily improved over the past decade, and they now possess properties that make them competitive in many respects with their metal-halide cousins [22,23,24].

Lamp efficacy is typically of the order of 70 lm/W, coupled with R_a values between about 55 and 80, and T_c in the region of 3000 K to 7000 K.

3.4.3 High Pressure Sodium-Vapour Lamps

The LPS (Low Pressure Sodium) lamp will be dealt with later in this chapter; but it may be noted at this point that its spectrum is virtually monochromatic, with about 90% of the visible radiant energy being concentrated in the doublet at 589,0 and 589,6 nm.

It was found that the colour characteristics of the sodium lamp could be considerably improved by increasing the pressure at which the sodium vapour is operated within the discharge tube.

An increase in pressure results in "Pressure-broadening" of the resonance doublet. Further increase in pressure results in further broadening accompanied by reabsorption of the resonance wavelengths. With a sufficient increase in pressure it is possible to produce a spectrum that is perceived as whitish in character (having a broadband spectrum) with a golden yellow cast to it.

This is the basis of the High Pressure Sodium-Vapour (HPS) lamp, the principle of which was known many years ago. It was not possible to produce it as a practical commercial proposition, however, until materials technology had advanced sufficiently to enable manufacturers to produce a translucent discharge tube, together with electrodes and electrode seals, that could withstand the highly corrosive attack of sodium vapour at high temperature and pressure, for a sufficient length of time to make a practical lamp with a reasonable life expectancy. These factors have been discussed by Lin [25].

Since its first commercial release some years ago, there has been a steady improvement in the technology associated with the HPS lamp – both in materials and in electrical operation (since it requires a high-voltage ignitor for initiating the discharge, as well as current-stabilizing control gear). One aspect of this project has been an experimental investigation of starting requirements of these lamps, making use of a variable-parameter ignitor circuit [26].

This lamp is now in widespread use in both exterior and interior lighting applications. Common exterior applications include roadway lighting and area flood-lighting such as railway goods yards, container terminals, etc. Common interior applications include the whole gamut of heavy and light industries. Projected improvements in its colour rendering properties will probably make it feasible to use this lamp in interior commercial and similar situations [27,28,29,30].

There has been some limited use of this lamp for sports flood-lighting, but there has been a general reticence (based presumably on its reputed poor colour rendering) to use it very widely; and there has been positive resistance to its use in applications where colour TV outside broadcasts may be implemented.

It is one of the aims of this document to argue that this resistance to the HPS lamp is now unjustified. It has a good luminous efficacy (100 lm/W) and is reputed to have extremely long life (24000 hours) and excellent lumen maintenance (90% at end of life).

Its colour rendering index (around 20 in the CIE system) would seem rather poor, but it is suggested that this figure underrates its real colour capabilities, since there seems to be some degree of "adaptation" to its colour properties after a suitable period of adjustment. It is the opinion of informed sportsmen that the colour rendering of this source is adequate for all normal sporting requirements – including discrimination between team colours of opposing teams, even in fast sports such as hockey.

This leaves the only real objection to HPS as its suspect colour reproduction properties when used as the illuminant for colour TV broadcasts. It is argued that, with the improvements that have taken place in the design and operation of these lamps, and in the flexibility and sensitivity of modern TV systems, there is no longer any real impediment to the use of HPS sources as scene illuminants in Colour Television OB situations. It is true, however, that special alignment procedures would have to be implemented to permit the use of colour TV equipment in conjunction with this lamp.

HPS deluxe lamps have recently been released on the market, but the author has no personal experience of their properties or performance. They are expected to have a somewhat reduced luminous efficacy, coupled with an increase in R_a and T_c, and may yet prove to be highly suitable for colour TV applications.

One of the perennial problems faced by users of HPS lamps is their tendency to "cycle" which seems to increase in probability as the lamps age, and which appears to be aggravated by thermal effects within luminaires [31]. This problem comes about as a result of an excessively high arc voltage which leads to the lamp's being extinguished, followed by reignition after a short period of cooling. This cycling will continue indefinitely until (usually) the failure of the electronic ignitor circuit.

3.5 MODERN LOW PRESSURE LAMPS

3.5.1 Low Pressure Sodium-Vapour Lamps

The LPS (Low Pressure Sodium) lamp, originally marketed in the 1930's and 1940's, has always been the most efficient of all electric lamps. Lamps of this type now have luminous efficacies in the region of 150 to 180 lm/W. However, the colour rendering properties of the LPS lamp are extremely poor – in fact, it tends to render all lit scenes monochromatically, so that most colours are totally distorted and are perceived merely in terms of "degrees of lightness".

This is because this type of lamp produces a resonance spectrum that concentrates practically all the visible radiation into the doublet at 589,0 and 589,6 nm. The light output is therefore perceived as a monochromatic yellow-orange hue, and everything lit by it is seen in shades of this hue.

This type of lamp is therefore totally unsuitable for any colour reproduction application, although it would be possible to employ it successfully in monochromatic (Black-and-White) image reproduction systems provided that the spectral sensitivity of the pickup device were suitable.

3.5.2 Fluorescent Tubes (Low Pressure Mercury-Vapour Lamps)

The fluorescent tube has a low-pressure filling of mercury vapour. The operating pressure is chosen for optimum generation of the mercury resonance line at 254 nm. Internally, therefore, the fluorescent tube is an efficient source of high energy ultraviolet radiation (UV-C).

In normal use, the user is protected from this UV by the absorption of the glass tube, together with the fact that the great majority of the UV energy is absorbed by the internal coating of phosphor material before reaching the inner surface of the glass.

A small proportion of the energy of the discharge is radiated at the other wavelengths characteristic of mercury, including those in the visible range. These latter make a minor contribution to the colour and light-output characteristics of the lamp; but by far the major influence in this regard is the selection of phosphor material for the internal coating of the tube.

The halophosphates have traditionally been chosen for this purpose, and they have led to lamps that have acceptable properties at moderate cost for general purpose lighting. The luminous efficacy is usually around 60 lm/W, coupled with middling colour rendering properties (R_a between about 50 and 70) and a wide range of colour appearance (T_c from about 3000 K to 8000 K).

Improvements in colour rendering were first sought by producing flatter SPD's in the so-called "deluxe" range of lamps. These yielded R_a values of up to about 95, but at greatly reduced efficacies (around 30 lm/W) so they were seldom economically justifiable.

More recent developments with phosphor materials have led to the so-called "Triphosphor" or "Three Band" type of lamp [32–35]. As these names imply, the phosphor is a mixture of three components, each of which has a peak output in a different part of the spectrum (red, green and blue outputs).

These lamps possess high efficacies (around 70 to 100 lm/W) coupled with high values of R_a (above 80) and they appear to be capable of functioning very effectively as taking illuminants for colour reproduction systems. The author was initially encouraged in this regard by a very successful series of photographic experiments, and took steps to ensure that triphosphor sources were included in the television experiments described in Chapter 5 – from which it will be evident that these lamps offer great promise for television lighting, particularly in situations where lighting of a diffuse character may be desirable or acceptable. One possible area of application that comes to mind is in teleconference facilities.

3.6 SUMMARY AND CONCLUSIONS

This chapter has reviewed the range of lamps currently available to the modern lighting designer, and has considered their potential applications in colour reproduction applications, while questioning some of the conventional wisdom in this sphere.

In the light of this study, there would appear to be some justification for a controlled experiment aimed at a determination of the colour reproduction properties of these new light sources. Such an experiment is described in detail in Chapter 5.

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CHAPTER 4

COLOUR MEASUREMENT SYSTEMS AND THE UND SPECTROPHOTOMETER

4.1 INTRODUCTION

This chapter will review briefly some of the requirements and design features of colorimeters in general, and will then present details of the design and performance of the UND spectrophotometer (i.e. the system constructed as part of this project).

4.1.1 The Need for Colour Measurement and Specification

The need for colour measurement and specification is founded on the fact that so many products and services offered by modern commerce and industry are distinguished by their inherent colours or by their ability to enhance, modify, reflect or reproduce colours.

The need for colour specification may arise, for example, when it is necessary to ensure colour uniformity of a product line.

The necessity for colour measurement then follows in order to maintain colour quality control of the specified products. Such a situation is very common in the textile and clothing industries, and it may also arise in many other industries such as the pulp and paper industry, the paint industry, the plastics industry, the pharmaceuticals and food preparation and processing industries, the building industry, the motor industry, and many others. Any consumer or user of these types of products will probably regard as axiomatic the need to be able to match the colours of such products (even if acquired from different production batches at different times) preferably by means of an unambiguous colour specification. The motorist whose car is involved in a collision and needs repairs is a prime example. How often is it that the panel-beater can offer him a spray-paint finish that is a truly acceptable match to the original?

In the lighting industry, there is a need to be able to specify both the colour appearance and the colour rendering properties of the electric lamps in common use; while in the advertising industry, and in the colour reproduction industry generally, there is a need to be able to specify and monitor the performance of colour reproduction systems such as colour television, colour photography and colour printing, and to specify the light sources for use in conjunction with such processes. In the transportation industry, it is necessary to be able to specify and to measure the colours of painted surfaces and retroreflectors, as well as light sources used for traffic control, signalling, navigation and aviation, and warning purposes.

Because of the importance of colour in so many facets of life, domestic and social as well as commercial, professional and industrial, it is difficult to devise a really comprehensive list of situations that call for colour specification or measurement. However, the foregoing discussion summarizes those areas where colour specification is probably of the greatest value.

4.1.2 Colorimetric Requirements of the Project

It was considered that it was necessary, in assessing the performance of a colour reproduction system, to be able to measure the colour characteristics of light sources and of scene elements and their reproductions, under a variety of controlled conditions.

It has therefore always been a primary objective of this work to be in a position to quantify, as accurately and repeatably as possible within a reasonable budget, all the test colours and their reproductions in the experimental test set-up.

In saying this, there is no intention of denying the importance of the subjective approach to the assessment of the performance of a colour reproduction system (and this will be stressed in the next Chapter). However, there is also much to be said for the quantitative approach which permits one to define colours in reasonably precise numerical terms.

4.1.3 Principles of Light and Colour Measurement

The general principles of light and colour measurement have been dealt with in detail in Chapter 2. The following is a brief restatement of cardinal aspects, together with an introduction to the different techniques whereby these principles are put into practice.

Light and colour are not essentially physical quantities. Rather they represent human responses to physical stimuli. However, thanks to the use of the CIE ($\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$) colour matching functions, it is possible to make purely physical measurements of light and colour stimuli which yield data that can then be converted to forms that represent subjective human experience – hence the term “psychophysical” as a generic name for these variables.

Two sets of colour matching functions have been defined by the CIE: these are the 2-degree and 10-degree sets. By convention, the 2-degree functions $(\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda)$ are employed when measuring colours for which the visual subtense is 4 degrees or less; and the 10-degree functions $(\bar{x}_{10\lambda}, \bar{y}_{10\lambda}, \bar{z}_{10\lambda})$ are to be preferred when the visual subtense is more than 4 degrees.

As seen in Chapter 2, the methods of defining, specifying and measuring colour are based in principle on colour matching techniques. In practice, however, they often employ spectral analysis and numerical integration techniques instead. Various simplifications and extensions of these processes exist, and many different approaches – differing in detail though not in principle – have been implemented in different colorimeter systems.

Figure 4.1 illustrates the general principles that are embodied in all forms of colorimeter, while Figure 4.2 shows how colorimeters may be broadly classified into three groups: viz. Spectrophotometric, Tristimulus (photoelectric), and Visual-matching types. These are discussed further in the following paragraphs.

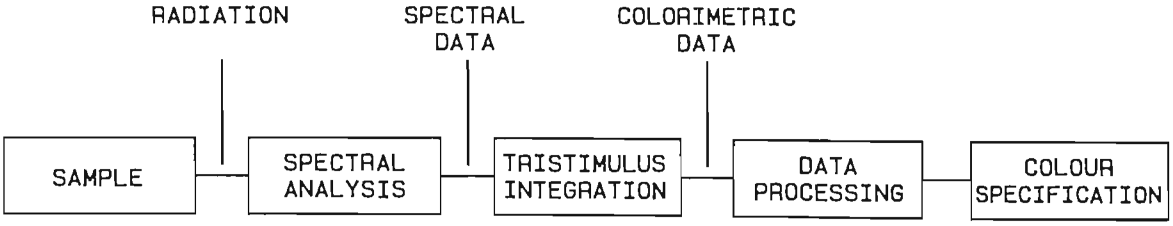

FIGURE 4.1: ELEMENTS OF THE GENERALIZED COLORIMETER

The sample may be a light source, or a light modifier (i.e. a reflecting or transmitting surface) that requires to be illuminated by a standard source.

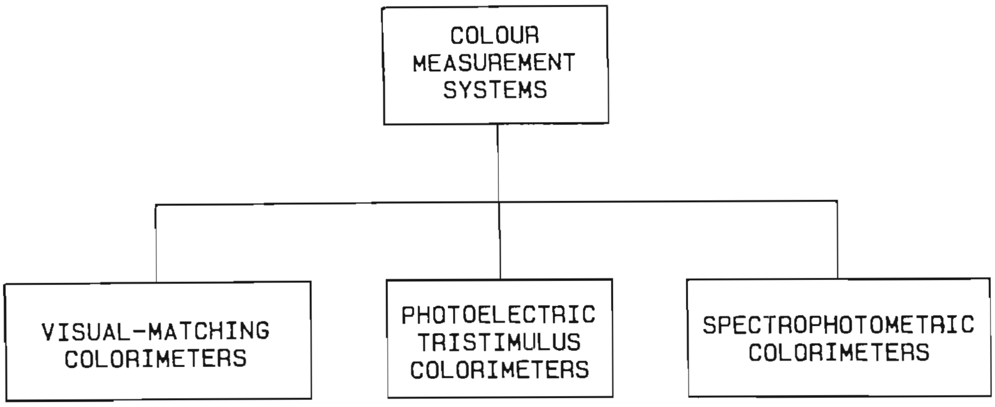

FIGURE 4.2: CLASSIFICATION OF COLOUR MEASUREMENT SYSTEMS

All three systems aim at providing the same colorimetric data, but they differ in accuracy, repeatability, and convenience.

(i).Spectrophotometric Colorimetry:

The fundamental approach to the measurement of the psychophysical variables involves measuring the physical spectrum of the particular stimulus. This is termed the spectrophotometric approach to colorimetry. In this case, the conversion to psychophysical data is done numerically, usually with the aid of digital computers, to obtain correlation integrals of the spectral stimulus function with each of the three colour matching functions:

$$X = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{x}_{\lambda}\, d\lambda$$

$$Y = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{y}_{\lambda}\, d\lambda$$

$$Z = k \int_{360\text{nm}}^{780\text{nm}} \phi_{e\lambda}\, \bar{z}_{\lambda}\, d\lambda$$

where k is a constant for the set
and $\phi_{e\lambda}$ is the spectral radiant flux of the test stimulus.

In practice, these integrals are usually evaluated numerically:

$$X = k \sum_{360\mathrm{nm}}^{780\mathrm{nm}} \phi_{e\lambda} \bar{x}_\lambda \, d\lambda$$

$$Y = k \sum_{360\mathrm{nm}}^{780\mathrm{nm}} \phi_{e\lambda} \bar{y}_\lambda \, d\lambda$$

$$Z = k \sum_{360\mathrm{nm}}^{780\mathrm{nm}} \phi_{e\lambda} \bar{z}_\lambda \, d\lambda$$

These summations yield the tristimulus values which, as a set, represent a complete psychophysical description of the measured stimulus. Psychophysical data can be computed in several different forms that correspond in varying degrees with subjective (psychometric) colour scales. This aspect was discussed fully in Chapter 2.

(ii).Tristimulus – Photoelectric Colorimetry:

Another approach is to carry out the spectral correlations optically by the use of filters. This produces three measured variables (usually voltages or currents) that are the direct analogs of the tristimulus values. The measurement process is therefore greatly simplified, but its accuracy is strongly dependent on the goodness-of-fit of the detectors (plus filters) to the colour matching functions. Good tristimulus filters are usually difficult and expensive to produce. This technique is used in tristimulus colorimeters of various types, and it also forms the basis (roughly speaking) of the colour analysis stage of modern television cameras. A special case of this technique involves the use of only one filter to represent the $\bar{y}_\lambda$ colour matching function (the same as the V_λ standard visibility function) to yield a measurement of incident *light*.

(iii).Visual – Matching Colorimetry:

Here, the spectral correlations are performed automatically by the inherent responses of the human observer. In order to obtain a numerical representation of the unknown colour, it is necessary for the observer to set up a colour match between two halves of the visual field – one half being the unknown colour, and the other half containing a selectable mixture of three (usually) primary colours. Once a match has been achieved, the proportions of the primaries in the mixture determine the specification of the unknown colour.

It is necessary for the primaries to be defined in CIE terms if it is required to compute the specification of the unknown in standard quantities.

(iv).Colorimeter Applications:

Spectrophotometers and tristimulus colorimeters are likely to find application in those industries mentioned in Section 4.1.1, where colour is an important attribute of the product. Where on-line monitoring is required, it is more common to employ tristimulus principles (i.e. filtered photocells) to detect the light transmitted, reflected or produced by a particular product. Off-line quality checks are perhaps better served by the spectrophotometry approach, particularly where the test duration is not a critical factor, and where high accuracy and repeatability may be demanded.

Portable lightmeters for photography and for the field assessment of lighting installations, generally make use of single, spectrally-corrected photocells.

4.2 COLORIMETER SYSTEMS

In this Section, further details will be given of the different varieties of colorimeter that were introduced above.

4.2.1 Spectrophotometers

General outlines of the structure and operation of a spectrophotometer system are given in Figures 4.3 and 4.4.

FIGURE 4.3 : FUNCTIONAL BLOCK DIAGRAM OF A TYPICAL SPECTROPHOTOMETER

Illustrating the principles involved in the spectrophotometric approach to colorimetry.

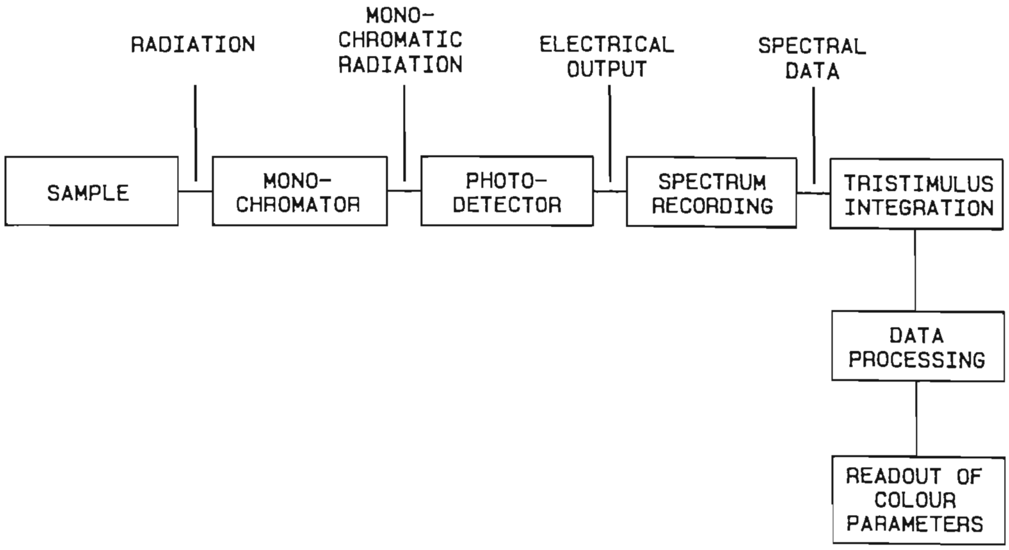

FIGURE 4.4 : GENERALIZED SYSTEM STRUCTURE OF A TYPICAL SPECTROPHOTOMETER

Showing the various stages of a spectrophotometer system.
(See text for details.)

A monochromator is used to analyse the incoming radiation (received from the sample) into its spectrum. This spectrum is usually sampled, one wavelength band at a time, and an electrical analog of the spectral radiant flux is produced by a suitable photodetector, usually a photomultiplier tube.

This type of detector is generally spectrally selective in the sense that its sensitivity changes with wavelength, and so it is usually necessary to calibrate it against some suitable standard. For spectral reflectance measurements, the standard is normally a good, diffuse white reflector (such as Barium Sulphate whose spectral reflectance characteristics are now well known) while for SPD measurements on sources it would be necessary to calibrate against a standard source of known SPD. It is clear, therefore, that spectral measurements of this type are obtained on the comparison principle.

The measurements of the spectrum can be recorded in several ways (eg manually, graphically, or direct into computer memory). Once the data on the complete spectrum is available the three tristimulus integrals can be evaluated (normally by numerical means and usually on a digital computer) to yield the tristimulus values X, Y, Z. From these, the chromaticity coordinates can readily be determined. Where a computer program is used to evaluate X, Y, Z, it can easily be extended to calculate the psychometric colour parameters as well as the chromaticity coordinates.

4.2.2 Photoelectric Colorimeters

General outlines of the structure and operation of a tristimulus photoelectric colorimeter are given in Figures 4.5 and 4.6.

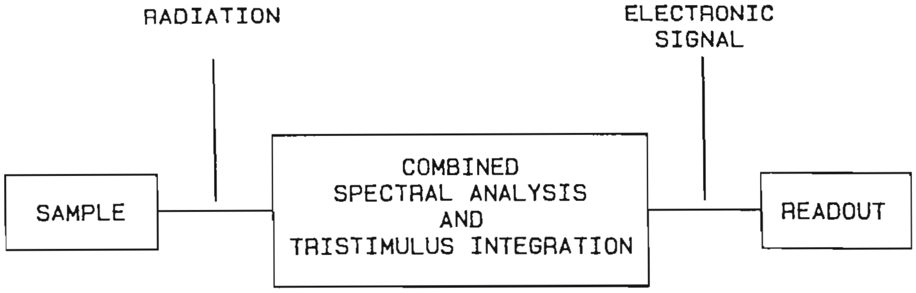

FIGURE 4.5 : FUNCTIONAL BLOCK DIAGRAM OF A PHOTOELECTRIC TRISTIMULUS COLORIMETER

Illustrating the principles involved in photoelectric colorimetry.

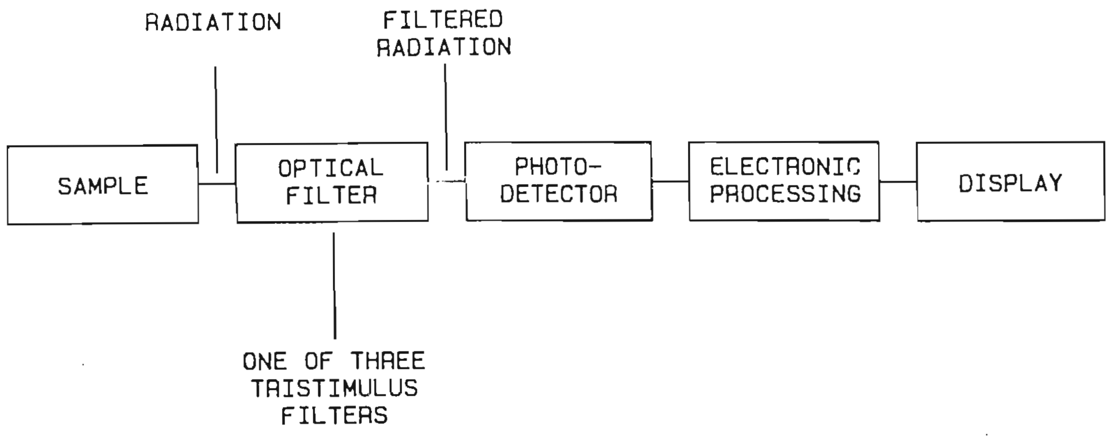

FIGURE 4.6 : GENERALIZED SYSTEM STRUCTURE OF A PHOTOELECTRIC TRISTIMULUS COLORIMETER

Showing typical form of implementation. (See text for details.)

The light from the sample enters the detection system via a set of optical filters. These filters are designed to emulate, in conjunction with the spectral response function of the photo-detector, the three CIE colour matching functions ($\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$).

The light passing through each filter thus evokes a response from the detector that is a direct representation of the corresponding tristimulus value.

The usual arrangement is to use a single detector to measure X, Y and Z in sequence by sampling the radiation through each filter in turn.

Once the tristimulus values for a particular sample are known, it is a matter of simple algebraic manipulation to obtain the chromaticity coordinates or psychometric colour parameters. Many of the more sophisticated commercial instruments of this family incorporate three detector heads and simple analogue computers to calculate and display a direct readout of the (x,y) chromaticity coordinates. One may anticipate the increasing use in the future of microprocessors to compute and display values of practically any CIE colour parameter almost instantaneously after completion of the required three readings.

4.2.3 Light Meters

General-purpose light meters can be regarded as a sub-class of photoelectric colorimeters. A simple light meter generally makes use of a single photoelectric cell which has been spectrally corrected (by filtration) to match the $\bar{y}_\lambda$ (or V_λ) spectral sensitivity curve since it is usually required to measure in photometric units such as the lumen (lm) or in other units which are simply related to the lumen, such as the lux (lm/m^2), the candela (lm/sr), or the nit ($lm/sr\text{-}m^2$).

It is now common to employ silicon photovoltaic cells in such instruments, and selenium cells were widely used in the past. Where the cell current is sufficiently great, the readout can be obtained directly on a moving-coil instrument, although it is now more common to use DC amplifier circuits, usually incorporating current-to-voltage converters, to drive various forms of readout device, of which the most popular now appears to be the digital liquid-crystal display.

Photographic light meters do not necessarily have to conform spectrally to the V_λ visual weighting curve. They should, ideally, possess filtration characteristics that confer a spectral sensitivity function that matches that of the specific film in use. Because of the complexity and cost of this approach, it is seldom (if ever) used in practice. Photographic light meters often make use of uncorrected (i.e. unfiltered) photocells and they may have relatively broad spectral sensitivity curves that embrace (but are not restricted to) the visible range of wavelengths.

4.2.4 Visual Colorimeters

General outlines of the structure and operation of a visual colorimeter are given in Figures 4.7 and 4.8.

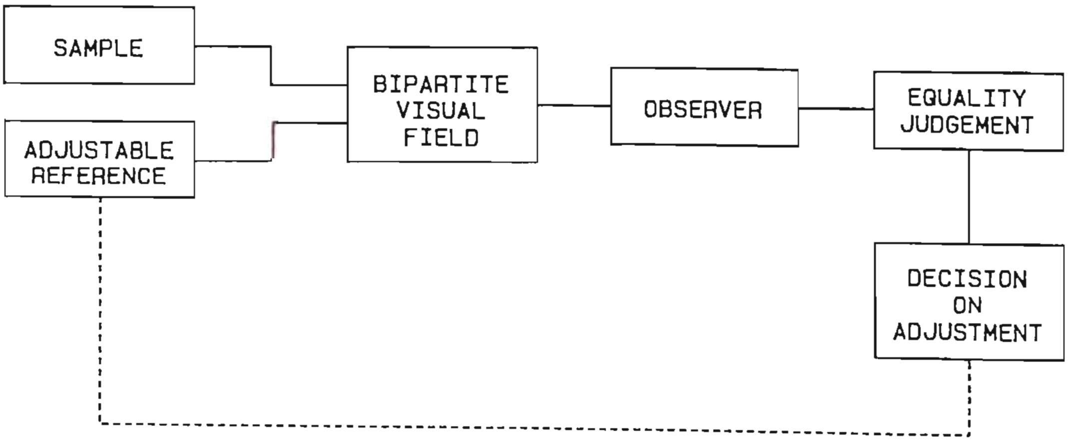

FIGURE 4.7 :
FUNCTIONAL BLOCK DIAGRAM OF A VISUAL COLORIMETER
Illustrating the principles involved in visual colorimetry.

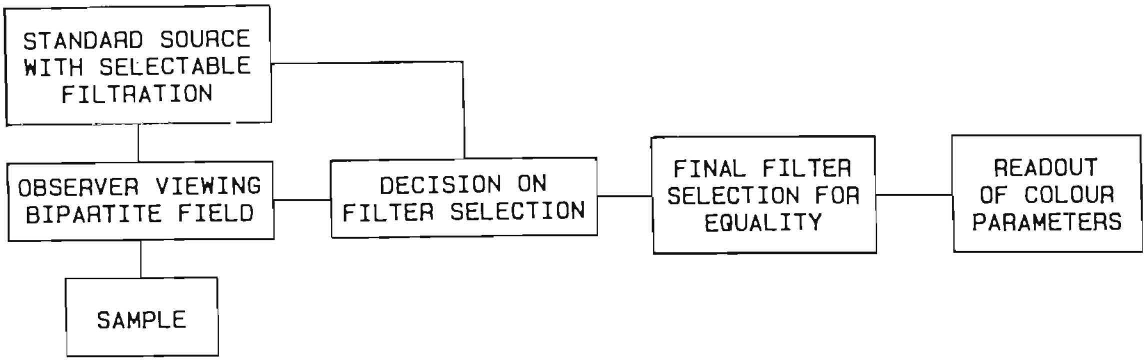

FIGURE 4.8 :
GENERALIZED SYSTEM STRUCTURE OF A VISUAL COLORIMETER
Showing typical form of implementation. (See text for details.)

The light from the sample is compared visually by the operator with that from a standard filtered source. The filtration of this source is adjustable so as to permit the operator to achieve a match with the sample.

Knowing the characteristics of the source and the filters, it is possible to determine the numerical specification for the sample colour from the filter combination that is required to achieve a perfect match between the two halves of the visual field.

The inherent $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ responses of a colour-normal human operator are thus employed to effect a metameric match between the unknown colour and the synthesized matching field.

The two half-fields should, ideally, be separated by as small a distance as possible, and the angular subtense of the total visual field should be at least 1 degree but may be larger if required in terms of the specification for the measurement. (If larger than 4 degrees, then the observer will achieve a match closer to that corresponding to the $\bar{x}_{10\lambda}$, $\bar{y}_{10\lambda}$, and $\bar{z}_{10\lambda}$ colour matching functions).

4.3 SELECTION OF COLORIMETER SYSTEM

4.3.1 Visual Colorimeters

Based on the experience gained over a number of years in the use of different types of colorimeters [1, 2, 3] the writer has formed the opinion that visual colorimeters are extremely useful as educational tools, but that very great care is necessary if accurate and repeatable colour measurements of scientific or commercial precision are to be achieved. In fact, when measurements were made by more than one operator on the Tintometer visual colorimeter in the author's laboratory, the problem of correlating their measurements was found to be an almost impossible task.

Other forms of visual colorimeter do exist, but it is considered unlikely that any small-field instruments will yield significant improvements in performance.

It was therefore decided not to make use of the visual colorimeter for any critical measurements in this project, but to use it only when convenience dictated its use for approximate measurements.

4.3.2 Tristimulus Colorimeters

The two tristimulus colorimeters of which the author has had some personal experience were both relatively simple to use, and yielded data of good repeatability and accuracy. Of the two, the CSIR Mask Colorimeter [4] possessed noticeably the better performance, and could have been relatively easily adapted to measure either the colours on a television monitor or the surface colours of reflecting samples. The Colormaster filter colorimeter [5], on the other hand, was built specifically to make surface colour measurements of reflecting materials, and was simple to operate in this mode. It would not, however, be easy to adapt this particular instrument to make colour measurements of monitor screens. Other makes of instrument may be more readily adaptable, but it was felt that all were likely to suffer from colorimetric errors as a result of small mismatches between the filter transmittances and the required colour matching functions.

If one were to choose to use a tristimulus colorimeter in this work, therefore, the mask colorimeter type would appear to be the logical choice. However, in view of the fact that this type of instrument employs a spectral dispersion system (i.e. prism or grating) as an essential feature of its construction, there is little or no cost or performance benefit to be gained from its use as compared with a simple spectrophotometer system. Its major advantage is speed of operation since only three readings (and no numerical integrations) are required in order to obtain the desired tristimulus values.

The spectrophotometer does, however, possess other attractive characteristics (see Section 4.3.3 below) and it was accordingly decided to employ this type of system for the colorimetric work required in this project.

4.3.3 Spectrophotometric Colorimeters

A spectrophotometer is a system of some complexity, and a measure of care is necessary to ensure that it yields measurements possessing useful gains in accuracy and precision when compared with the simpler forms of colorimeter already described. Provided that this kind of care is exercised, the spectrophotometer generally outperforms the other classes of instruments.

In addition, the spectrophotometer, as the name implies, relies for its operation on the measurement of the spectrum of the test sample. A great deal more useful information about the nature of the test sample is gleaned by this approach and, in the case of light sources, it is the only practical way to obtain information on colour rendition properties, since the tristimulus values (X,Y,Z) yield only information describing the colour appearance of the source.

The decision was thus taken to employ a spectrophotometer system for the colour measurement work in this project in view of the advantages it offers over the other types of instruments.

4.4 THE UND SPECTROPHOTOMETER SYSTEM

4.4.1 Introduction

The factors discussed in the last section led to the design and construction of an automated spectrophotometer system directed specifically at the needs of the colour reproduction research programme, but also sufficiently flexible to be able to offer a general service to local industry in the spectral measurement of light sources and in the spectrophotometric testing of materials [6].

In order to provide for as many as possible different forms of spectrophotometry, is was decided to design the optical, electrical and electronic systems comprising the spectrophotometer to be adaptable to different configurations and to be operated , in most cases, in either manual or automatic modes.

4.4.2 Design Features

The following is a brief outline of the major design features of the spectrophotometer (see also Figure 4.9).

(a) The heart of the system is a Monochromator. A grating-type dispersion system was chosen for its linearity.

(b) A double monochromator configuration was selected for its low stray-light characteristics.

(c) A system using two separate monochromators was chosen for flexibility. This permits the two monochromators to be used independently, and it can also be useful for fluorescence studies, when one monochromator is used as a UV illuminator and the second can determine the emitted spectrum of the phosphor.

(d) Photomultiplier tubes (PMT's) were chosen as the light detectors, and different units are available for different spectral ranges, one specially selected for its UV sensitivity.

(e) A programmable HT supply was selected for the PMT's, since the supply voltage can be used to control the gain and the S/N ratio of the detection system.

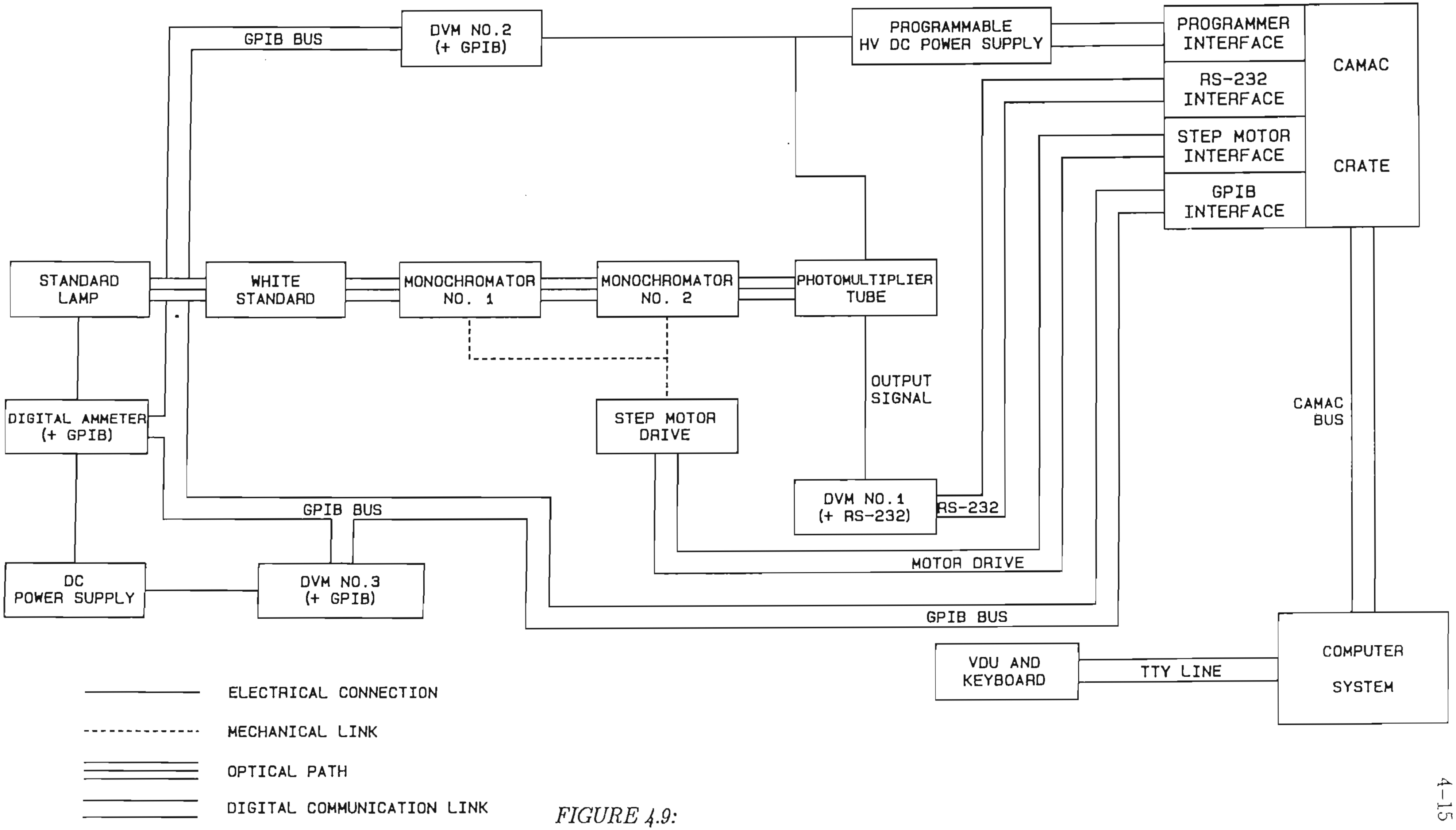

FIGURE 4.9:
THE UND SPECTROPHOTOMETRIC COLORIMETER

(f) A manually-set, automatically-monitored DC power supply is used for the standard lamps.

(g) The standard lamps have been calibrated in terms of spectral radiance values.

(h) The standard of surface whiteness is a compressed $BaSO_4$ tablet.

(i) The main readout device is DVM No.1 that reads the voltage across the PMT load.

(j) Three other digital multimeters are used for monitoring the PMT supply voltage and the power supplies to the Standard lamp.

4.4.3 Choice of Light-Detector

Despite the necessity for a stable high-voltage power supply in order to operate a PMT, it was decided to use this type of device in preference to semiconductor types. PMT's have advantages over semiconductors in several other respects, the chief of which are as follows [7,8].

(a) Spectral Response:

PMT's can be obtained with good sensitivities in the UV and visible ranges and the near-infrared (i.e. over the whole range 200 to 900 nm) while silicon cells are most effective in the IR range with very low sensitivity to UV and visible wavelengths in the region of 400 nm.

(b) Low Dark Current:

The dark current of PMT devices is much lower than that of Si devices – typically by a factor of the order of 10^6 to 10^9.

(c) Wide Dynamic Range and Linear Response:

The low noise of the PMT coupled with its high peak-current capability, makes it possible to obtain a linear response over a dynamic range of about 10^6 (120 dB) in terms of output current.

(d) High Gain:

PMT's are capable of providing inherent current gains in the region of 120 dB (c.f. approximately 40 dB for Si avalanche photodiodes and 0 dB for Si PIN photodiodes). Consequently, no additional amplification was required in the detection circuit.

(e) Gain Adjustment:

The gain of the PMT is readily adjustable by changing the supply voltage.

(f) Disadvantages:

(1) Because of the PMT's gain-sensitivity to supply voltage, it is imperative to employ a highly stable voltage source.

(2) PMT's are considerably less stable than PIN photodiodes, but their short-term stability is adequate for spectrophotometric purposes.

(3) Silicon devices can operate over a wider temperature range than PMT's, but this was not a consideration in this instance since the spectrophotometer system is situated in an air-conditioned laboratory.

4.4.4 Operation of the UND Spectrophotometer

Since the measurement is based on the comparison principle, the first step is to calibrate the response of the system at every wavelength within the range to be used.

Supposing that it is a light source (rather than a surface) that is to be measured, it is necessary, then, to employ a standard lamp possessing an output that is calibrated at each of the wavelengths to be used.

In this system, the standard lamp (usually a 150W or 250W, 24V projector lamp) is operated from a DC power supply and its current and voltage are monitored via a GPIB interface which samples readings taken on the digital ammeter and on DVM No. 3.

The light from the standard lamp is reflected off the white standard (the tablet of barium sulphate, which has near-uniform spectral reflectance over the visible range) and thence passes into the monochromator system which selects a very narrow band of wavelengths (of the order of 1 to 5 nm wide) centered on the wavelength selected by the mechanical drive system. The wavelength can then be selected under computer control by use of the stepper-motor or by a manual drive system.

The monochromatic light so obtained is passed on to the photomultiplier tube which is well screened from all ambient illumination. The volt drop across the photomultiplier's anode load is measured by DVM No. 1 and this voltage is directly proportional to the irradiation of the photomultiplier cathode at the selected wavelength (provided, of course, that the PMT is operating in its linear range, i.e. that the incident energy is at a sufficiently low level).

The reading of DVM No. 1 is passed to computer memory (via an RS-232 interface) where the spectral data are accumulated in a computer file from which they will later be accessed for further numerical processing.

The PMT is powered from an HV DC supply, the output voltage of which is monitored by DVM No. 2 which is also sampled via the GPIB interface. The HV DC is programmable to a limited extent (approximately 100 volts can be added to or subtracted from a fixed voltage in the region of 1 kV) in order to conduct experiments with variable PMT sensitivities and noise figures. The computer interface for this section has not yet been constructed, although manual programming is available.

The above systems have been interfaced to the Department's mainframe computer via a CAMAC system which reticulates throughout the building. However, because of the advantages of operating the whole system within a single laboratory, steps are now being taken to design a more compact, but similar, system around a desk-top computer.

Once the spectrum of the standard lamp has been measured, a repeat series of measurements is carried out using the test lamp in place of the standard lamp, and off-line computer programs are finally employed to calculate the radiant spectrum of the test source, from which its tristimulus values and chromaticity coordinates can also be computed.

In the case of surface colours, the spectral reflectance of the test surface is measured using the known reflectance of the barium sulphate tablet as standard. Otherwise, the procedures remain the same as for light sources.

4.5 ERRORS AND PRECAUTIONS

A concise and readable account of some of the more important factors falling under this heading has been given by Moore [9]. There are many sources of error possible in a spectrophotometer system. The most important of these are discussed here in general terms, which are then applied to the UND system.

4.5.1 Reference Lamp

When measuring the spectrum of a test *lamp*, the spectral radiance at each wavelength is obtained by simple proportion:

i.e. $$L_{et\lambda} = L_{eo\lambda} . V_{t\lambda} / V_{o\lambda} \qquad .....(4.5.1)$$

where $L_{eo\lambda}$ = spectral radiance of reference lamp

$V_{t\lambda}$ = output voltage reading obtained with test lamp

$V_{o\lambda}$ = output voltage reading obtained with reference lamp.

It is therefore important that $L_{eo\lambda}$ be known as accurately as possible, and that it be stable.

In the UND system, spectral radiance standards have been obtained from the CSIR. They are low-voltage tungsten-halogen lamps which are calibrated at a few percent undervoltage. These lamps have been checked by making periodic intercomparisons, and they appear to have maintained their calibrated values quite satisfactorily.

The lamp radiance is, of course, a function of lamp voltage and current. The lamp is run from a stabilized DC power source operated in constant-current mode, and its current and voltage are monitored continually throughout the test. The relevant digital meters are periodically calibrated against standards maintained in the Department.

When making measurements of test *surfaces*, an uncalibrated lamp is employed; but the requirements for stable operation and continual monitoring thereof remain as above.

4.5.2 White Standard

When measuring the spectral characteristics of a test *surface*, the spectral reflectance (or transmittance) factor is obtained by simple proportion:

i.e. $$R_{et\lambda} = R_{eo\lambda} \cdot V_{t\lambda} \,/\, V_{o\lambda} \qquad .....(4.5.2)$$

where $R_{eo\lambda}$ = spectral reflectance factor of reference surface

$V_{t\lambda}$ = output voltage reading obtained with test surface

$V_{o\lambda}$ = output voltage reading obtained with reference surface.

It is therefore important that $R_{eo\lambda}$ be known as accurately as possible, and that it be stable.

In the UND system, the spectral-reflectance-factor standard is provided by the use of a tablet of pressed $BaSO_4$ powder for which accurate calibration figures are available. When not in use, this tablet is kept carefully covered and is stored inside a desiccator. Several of these tablets have been checked by periodic intercomparisons, and $R_{eo\lambda}$ values have been found to be highly stable.

When making measurements of test *sources*, an uncalibrated white diffuser is employed in place of the calibrated $BaSO_4$ tablet. The only requirement is that the properties of this white surface remain stable over the period of the measurement of the test sample and the standard source (i.e. between about 15 and 60 minutes normally).

4.5.3 Wavelength Errors

The accuracy and linearity of the wavelength drive are critical in the avoidance of wavelength errors – as also is the setting of the diffraction grating within its mount. A precision of ± 0,0001 in u' and v' in the central region of the chromaticity diagram corresponds to a wavelength accuracy of about ± 0,2 nm over the visible range (deduced from Reference [9]).

Mechanical backlash is avoided by running the wavelength drive in only one direction while taking readings, and then rewinding to the starting point once the complete spectral range has been covered.

Wavelength settings can be easily checked by using the mercury spectrum that is present in the fluorescent room-lights.

When operating in the Double-Monochromator mode, the wavelength tracking of the two units is again set and checked by reference to the mercury spectrum.

4.5.4 Second-Order Diffraction

In a grating-type monochromator, higher-order diffraction spectra occur at settings corresponding to integer-multiples of the actual wavelength; i.e. the monochromator will pass a wavelength λ when it is set at λ, 2λ, 3λ, etc. This means, for example, that when set to 780 nm, the monochromator output will be a combination of the 390 nm (relatively attenuated) and 780 nm content of the incoming spectrum; when set to 900 nm, it will be passing 300 nm, 450 nm and 900 nm; and so forth.

In making measurements covering the visible range (380 to 760 nm) on the UND spectrophotometer (and using a source whose spectral radiance is effectively zero below 300 nm) it is necessary to remove only the second order spectrum. This is achieved by the insertion of photographic UV-filters in the optical path. These filters cut in only at about 400 to 420 nm, so one is able to measure up to nearly 800 nm without having to use additional filters. For measurements below 400 nm, the filters are removed.

4.5.5 Stray light

Stray light is light that enters the photomultiplier's window without traversing the "proper" optical path through the monochromator.

It can occur as a result of light leakage through the monochromator or photomultiplier housings, or by multiple reflections off the grating and within the monochromator housing.

Stray light can be greatly reduced by operating in the double monochromator mode, and by taking steps to ensure that light leaks are kept minimal.

On the UND system, it has been found that stray light is almost negligible, even with a single monochromator. Fortunately, it appears to be independent of wavelength, so is probably due to light leakage, and it can be treated as an added component of "dark current".

4.5.6 Dark Current

Dark current is the electrical output signal produced by the photomultiplier tube in the absence of any incoming radiation. This is an unavoidable effect with any photomultiplier, and it appears as a constant offset superimposed on each spectral reading. It is a temperature-dependent effect, and can be greatly reduced by refrigerating the photomultiplier housing.

It was felt that, in Durban's humid climate, it would be preferable to avoid refrigeration unless it became absolutely necessary. The main advantage of refrigeration is an increase in the dynamic range of the detection system, improving the accuracy with which dark colours can be measured, particularly when operating with the double monochromator which has twice the attenuation (in dB) of a single monochromator. However, it has not so far been necessary to resort to refrigeration in this work.

In the UND system, the dark current is effectively removed by programming it as a constant offset which is automatically subtracted from the reading of DVM No. 1 (Figure 4.9).

This value is normally entered at the start of each spectral scan, and is checked at the end. Provided that the PMT has been allowed to stabilize for several hours prior to the measurement, there does not appear to be any dark current drift over the period of one spectral scan (i.e. about 5 to 15 minutes).

4.5.7 PMT Linearity

The validity of equations (4.5.1) and (4.5.2) as expressions of the measured spectrum depends to a large extent on the quantities $V_{t\lambda}$ and $V_{o\lambda}$ possessing the correct relative magnitudes – i.e. the linearity of response of the PMT.

PMT's typically possess linear characteristics (± 1 or 2 percent) over a 120 dB dynamic range. Improvements in linearity can be achieved by making use of graded (rather than uniform) inter-dynode voltages, and care must be taken to avoid excessive anode currents which lead to saturation effects and anode fatigue.

The UND system employs a graded dynode chain for improved linearity, and the output voltage across the anode load is not normally permitted to exceed 0,5 volt. Since the load resistance is 110 kΩ, this corresponds to an anode current of some 5 μA which is well within the specified current limit of 200 μA. In addition, the total dynode current was set at about 1,5 mA which was considered large enough to achieve linear operation without causing undue heating of the PMT housing.

4.5.8 Spectral Range

It is clear that the spectral-analysis and light-detection components of the system must operate satisfactorily over the wavelength range to be examined.

In the UND system, the spectrum analysis is performed using a pair of Jarrell-Ash model 82–410 0,25 metre Ebert monochromators [10] having the following spectral ranges:

200 to 450 nm using low-blaze [11] grating (2360 lines/mm);
350 to 900 nm using high-blaze grating (1180 lines/mm).

The overall efficiency of each unit is ≥ 40% for the wavelength ranges quoted above.

The spectral analysis system is thus capable of delivering useful levels of flux to the detection system over the range 200 nm to 900 nm.

The photomultipliers in normal use are two Thorn-EMI units:

– type 9848B with an extended-S20 spectral response (which covers the 350 nm to 900 nm range very satisfactorily);

– type 9659QB with a fused silica (quartz) window and a cathode with extended-S20 sensitivity (giving a usable spectral range of at least 200 nm to 900 nm) which was selected in order to permit possible future studies of UV spectra and of fluorescence phenomena.

Either one of these tubes can therefore be used for normal spectrophotometric colorimetry, although in practice the 9848B was found to be preferable for measurements in the visible region since it exhibited a higher anode sensitivity at most wavelengths of interest. The 9659QB is, of course, useful in any spectroradiometric applications in the visible plus near-UV and –IR ranges.

4.6 PERFORMANCE EVALUATION

Since the prime purpose of the UND spectrophotometer was to provide a reliable facility for colour measurement, it was decided to test its colorimetric performance against that of a similar, and well established, facility existing in the Precise Physical Measurements Division (now the National Measuring Standards and Metrology Division) of the CSIR in Pretoria. The spectral accuracy of the UND system can also be measured against the performance of the CSIR system, but it is less easy, in this instance, to draw concise and meaningful conclusions regarding the significance of the differences, if any, between the measured data on the two systems.

A set of 21 Munsell [12,13,14] colour samples (Figure 4.10) was initially selected from a Munsell Color File available to the author. Table 4.1 lists the Munsell Notations and the colour names for the samples (based on the ISCC-NBS [15,16] and Chroma-Cosmos 5000 [17] designations for the sample colours) together with the Munsell Renotation data obtained from Wyszecki and Stiles [18] and converted to the (Y,u',v') and (L^*,a^*,b^*) forms.

These 21 Munsell samples were initially measured on the CSIR spectrophotometer as part of the previously published work on the comparative performance of colorimeter systems [1,2,3]. This same set of samples was then subsequently measured on the UND spectrophotometer as a means of checking its performance. In both sets of measurements, the 45–degree/0–degree geometry was employed. Three separate sets of measurements were obtained on each instrument, and the results for Illuminant C are summarized in Table 4.2 in terms of (Y,u',v') and (L^*, a^*, b^*) coordinates. The data given in this table represents the arithmetic mean measured colour of each sample on each instrument.

The differences between the results achieved on the two instruments are tabulated in Table 4.3, and have been computed in the following forms, where subscript c signifies measurements on the CSIR system, and u on the UND system:

Luminance-Factor Differences:

$$\Delta Y = Y_c - Y_u \qquad .....(4.6.1)$$

Chromaticity-Coordinate Differences:

$$\Delta u' = u'_c - u'_u \qquad .....(4.6.2)$$

$$\Delta v' = v'_c - v'_u \qquad .....(4.6.3)$$

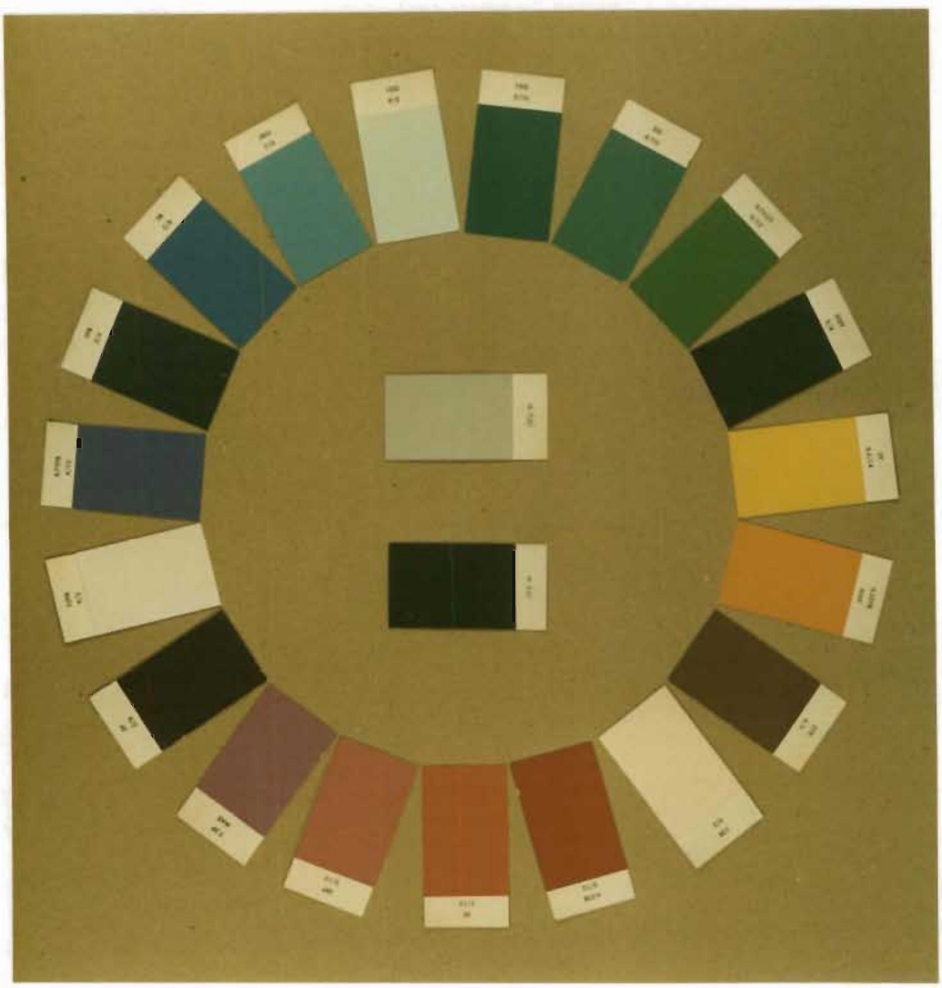

FIGURE 4.10: A PHOTOGRAPH OF THE 21 MUNSELL SAMPLES USED IN THE COLORIMETER PERFORMANCE EVALUATIONS

Sample No.1 is at the bottom, with reference numbers increasing anticlockwise to No.19. The neutral samples Nos. 20 and 21 are in the centre.
(Approximately 40% of full size)

Sample No	Munsell Notation	Colour Name (See Text)	Munsell Renotation Data for Sample					
			Y	u'	v'	L^*	a^*	b^*
1	5R5/12	Strong Red	19,77	,3486	,4941	51,60	50,74	26,60
2	6.25R3/12	Deep Yellowish Red	6,56	,4443	,5015	30,80	53,79	28,59
3	10R9/2	Pale Yellowish Pink	78,66	,2111	,4676	91,12	5,44	5,61
4	5YR4/4	Medium Brown	12,00	,2546	,5034	41,24	12,54	20,83
5	6.25YR7/16	Vivid Yellowish Orange	43,06	,3017	,5477	71,63	30,66	93,63
6	5Y8,5/14	Bright Yellow	68,40	,2342	,5546	86,24	-4,62	100,77
7	5GY3/4	Medium Olive Green	6,56	,1870	,5243	30,80	-13,04	21,97
8	8.75GY6/12	Vivid Yellowish Green	30,05	,1456	,5532	61,72	-51,82	56,74
9	5G6/10	Brilliant Green	30,05	,1311	,5001	61,72	-52,21	16,24
10	10G5/10	Strong Bluish Green	19,77	,1163	,4814	51,60	-51,99	4,45
11	10G9/2	Pale Green	78,66	,1865	,4661	91,12	-12,96	2,40
12	5BG7/8	Bright Blue Green	43,06	,1442	,4596	71,63	-39,20	-4,58
13	5B5/8	Strong Greenish Blue	19,77	,1391	,4026	51,60	-21,72	-26,65
14	5PB3/4	Greyish-Purplish Blue	6,56	,1788	,3969	30,80	2,23	-18,89
15	8.75PB4/12	Strong Purplish Blue	12,00	,1910	,3260	41,24	25,59	-46,49
16	10PB9/2	Pale Lavender	78,66	,2006	,4538	91,12	2,19	-4,96
17	5P2/8	Very Deep Purple	3,13	,2486	,3422	20,57	29,27	-25,03
18	7.5P4/12	Vivid Purple	12,00	,2604	,3666	41,24	43,61	-30,48
19	5RP5/10	Medium Purplish Red	19,77	,2885	,4400	51,60	42,47	-4,59
20	N7.5	Light Grey	50,68	,2009	,4609	76,52	0,00	0,00
21	N2.5	Dark Grey	4,61	,2009	,4609	25,61	0,00	0,00

TABLE 4.1 : COLOUR CHARACTERISTICS OF THE 21 MUNSELL TEST-COLOUR SAMPLES

The Munsell renotation data for the 21 samples used in testing the UND spectrophotometer.

Net Chromaticity Difference:

$$\Delta F\ (u',v') = [(\Delta u')^2 + (\Delta v')^2]^{1/2} \qquad .....(4.6.4)$$

Psychometric Lightness Difference:

$$\Delta L^* = L^*_c - L^*_u \qquad .....(4.6.5)$$

Psychometric Colour Coordinate Differences:

$$\Delta a^* = a^*_c - a^*_u \qquad .....(4.6.6)$$

$$\Delta b^* = b^*_c - b^*_u \qquad .....(4.6.7)$$

Psychometric Colour Difference (CIE–1976 (L^*,a^*,b^*) system):

$$\Delta E(L^*,a^*,b^*) = \Delta E^*(Lab) = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \qquad .....(4.6.8)$$

The data in Table 4.3 indicate rather good general agreement between the two instruments, with the values of $\Delta F(u',v')$ varying between 0,0002 and 0,0071 (mean 0,0019); ΔY between 0,0008 and 0,0352 (mean 0,0105); and $\Delta E^*(Lab)$ between 0,56 and 3,15 (mean 1,71). Referring to Table 4.2, one can discern a small, but fairly consistent, tendency of the UND spectrophotometer to show lower values of sample lightness (as measured by Y or L^*) and sample chromaticness (as measured by a^* and b^*).

Examining the components of ΔE^* namely ΔL^*, Δa^*, and Δb^*, it is seen that these are all of acceptably small magnitude, with the values of ΔL^* lying between 0,18 and 1,57 (mean 0,82); Δa^* between 0,03 and 1,92 (mean 0,91); and Δb^* between 0,02 and 2,46 (mean 0,89).

Sample No	Munsell Notation	(Y u' v') DATA						(L^* a^* b^*) DATA					
		CSIR S'PHOT			UND S'PHOT			CSIR S'PHOT			UND S'PHOT		
		Y	u'	v'	Y	u'	v'	L^*	a^*	b^*	L^*	a^*	b^*
1	5R5/12	19,25	,3552	,4933	18,32	,3529	,4937	50,99	52,60	26,46	49,90	50,94	26,04
2	6.25R3/12	5,81	,4654	,5075	5,60	,4584	,5066	28,95	54,51	33,00	28,38	52,75	31,33
3	10R9/2	76,72	,2112	,4680	76,18	,2113	,4687	90,21	5,38	5,86	89,98	5,18	6,33
4	5YR4/4	11,86	,2564	,5030	11,37	,2553	,5026	41,00	13,18	20,65	40,21	12,69	20,08
5	6.25YR7/16	41,78	,3019	,5476	39,65	,3010	,5474	70,73	30,49	92,75	69,24	29,62	90,29
6	5Y8,5/14	70,34	,2346	,5530	67,61	,2347	,5523	87,35	-3,92	97,76	85,84	-3,64	95,38
7	5GY3/4	5,84	,1867	,5259	5,68	,1877	,5246	29,02	-12,81	21,86	28,60	-12,20	21,12
8	8.75GY6/12	29,00	,1441	,5573	27,59	,1448	,5560	60,79	-52,88	60,48	59,55	-51,31	58,05
9	5G6/10	29,76	,1314	,5015	29,05	,1323	,5007	61,47	-52,05	16,94	60,85	-50,86	16,47
10	10G5/10	19,75	,1141	,4847	19,12	,1155	,4846	51,55	-53,98	5,82	50,84	-52,46	5,78
11	10G9/2	81,37	,1862	,4679	77,85	,1864	,4669	92,32	-13,60	2,92	90,75	-13,20	2,94
12	5BG7/8	43,29	,1440	,4626	41,68	,1449	,4637	71,77	-40,12	-2,92	70,68	-39,20	-2,23
13	5B5/8	19,70	,1382	,4035	19,06	,1390	,4047	51,51	-22,43	-26,28	50,78	-21,95	-25,53
14	5PB3/4	6,44	,1799	,3993	6,36	,1799	,4019	30,50	2,24	-18,06	30,32	1,80	-17,32
15	8.75PB4/12	11,41	,1914	,3405	11,22	,1910	,3451	40,27	21,45	-40,78	39,95	20,00	-39,06
16	10PB9/2	78,47	,2009	,4551	75,50	,2008	,4553	91,01	2,00	-3,97	89,66	1,87	-3,90
17	5P2/8	2,60	,2590	,3249	2,49	,2569	,3296	18,37	33,02	-26,91	17,88	31,23	-25,61
18	7.5P4/12	11,67	,2539	,3633	11,36	,2515	,3660	40,71	41,66	-31,51	40,20	39,74	-30,45
19	5RP5/10	19,16	,2948	,4403	18,52	,2935	,4412	50,89	44,39	-4,12	50,14	43,16	-3,73
20	N7.5	52,29	,2011	,4616	50,54	,2011	,4619	77,47	0,00	0,38	76,43	-0,11	0,58
21	N2.5	4,57	,2005	,4619	4,37	,2002	,4616	25,48	-0,22	0,25	24,88	-0,25	0,13

TABLE 4.2 :
MEASURED SAMPLE COLOURS EXPRESSED IN CIE-1976 COORDINATES

Computed for Illuminant C
from the average spectral reflectances measured on the CSIR and UND instruments

Sample No	Munsell Notation	Differences Between Measured Results (CSIR data - UND data)							
		ΔY $(x10^{-4})$	$\Delta u'$ $(x10^{-4})$	$\Delta v'$ $(x10^{-4})$	$\Delta F(u',v')$ $(x10^{-4})$	ΔL^* $(x10^{-2})$	Δa^* $(x10^{-2})$	Δb^* $(x10^{-2})$	$\Delta E(L,a,b)$ $(x10^{-2})$
1	5R5/12	93	23	-4	23	109	166	42	203
2	6.25R3/12	21	70	9	71	57	176	167	249
3	10R9/2	54	-1	-7	7	23	20	-47	56
4	5YR4/4	49	11	4	12	79	49	57	109
5	6.25YR7/16	213	9	2	9	149	87	246	300
6.	5Y8.5/14	273	-1	7	7	151	-28	238	283
7	5GY3/4	16	-10	13	16	42	-61	74	105
8	8.75GY6/12	141	-7	13	15	124	-157	243	315
9	5G6/10	71	-9	8	12	62	-119	47	142
10	10G5/10	63	-14	1	14	71	-152	4	168
11	10G9/2	352	-2	10	10	157	-40	-2	162
12	5BG7/8	161	-9	-11	14	109	-92	-69	158
13	5B5/8	64	-8	-12	14	73	-48	-75	115
14	5PB3/4	8	0	-26	26	18	44	-74	88
15	8.75PB4/12	19	4	-46	46	32	145	-172	227
16	10PB9/2	297	1	-2	2	135	13	-7	136
17	5P2/8	11	21	-47	51	49	179	-130	227
18	7.5P4/12	31	24	-27	36	51	192	-106	225
19	5RP5/10	64	13	-9	16	75	123	-39	149
20	N7.5	175	0	-3	3	104	11	-20	106
21	N2.5	20	3	3	4	60	3	12	61

TABLE 4.3 : CHROMATICITY DIFFERENCES (ΔF) AND COLOUR DIFFERENCES (ΔE) BETWEEN THE TWO INSTRUMENTS

Computed from the data given in Table 4.2 using equations (4.6.1) to (4.6.8).

Parameter	Colour Sample Yielding Maximum Value	
	Reference No.	Munsell Notation
ΔF	(2)	6.25 R 3/12
ΔY	(11)	10 G 9/2
ΔE^*	(8)	8.75 GY 6/12
ΔL^*	(11)	10 G 9/2
Δa^*	(18)	7.5 P 4/12
Δb^*	(5) (8)	6.25YR 7/16 8.75 GY 6/12

TABLE 4.4 : SAMPLE COLOURS ASSOCIATED WITH HIGHEST DEVIATIONS BETWEEEN THE CSIR AND UND SPECTROPHOTOMETERS

Table 4.4 lists those sample colours which gave maxima for one or more of the foregoing parameters.

It is interesting that ΔY and ΔL^* are both largest for sample No. 11 (10G9/2) which has a Munsell value of 9, corresponding to a reflectance of some 80%. In other words, the lightness parameters Y and L^* were measured with least repeatability on one of the lightest samples.

In all the other cases, the parameters concerned represent (or include) sample chromaticness, and here it is of interest to note that the samples involved are all highly chromatic (or, highly saturated) having a Munsell chroma of 12 or higher.

These observations led to attempts to correlate the relative magnitudes of these colour difference parameters with the chief appearance attributes of the test samples (viz. the Munsell Hue, Value and Chroma parameters) using the techniques developed previously [3]. Statistically significant correlations were observed between the following pairs of variables:

ΔY and Value

ΔL^* and Value

ΔE^* and Chroma.

There was also some slight evidence of a correlation between ΔY and $(\text{Value})^{-1}$; and there appeared to be no correlation at all between Hue and any of the colour difference parameters.

These findings accord closely with those reported in Reference [3] and, as stated there, are probably indicative of the influence of small wavelength errors, and perhaps also of small nonlinearities.

An investigation was also carried out of the repeatability of the UND spectrophotometer. This was facilitated by the fact that each test colour had been measured three times on this instrument, so that it was possible to assess the standard deviations (s) in the measurements so taken, and to determine their correlation with the Munsell notation data. The measured data have been expressed in the (Y,u',v') and (L^*,a^*,b^*) systems, as set out in Table 4.5.

Each of the three measurements of each sample on the UND system has been expressed in terms of the six coordinates (Y,u',v') and (L^*,a^*,b^*). Note that Y is here taken to be a fraction, so that Y, u' and v' are always positive numbers in the range from zero to unity; while L^*, a^* and b^* are all unbounded numbers of either sign, but with magnitudes generally in the range between zero and one-hundred.

One may therefore arrive at the standard deviation in the measurement of each of the six coordinates for each test sample. These six standard deviations may be expressed as:

$s(Y)$, $s(u')$, $s(v')$ and $s(L^*)$, $s(a^*)$, $s(b^*)$.

Since standard-deviation is in itself a root-mean-square (rms) quantity, it would seem logical to combine each group of three such terms in rms fashion.

Thus $$s(Y,u',v') = [s^2(Y) + s^2(u') + s^2(v')]^{1/2} \qquad .....(4.6.9)$$

and $$s(L^*,a^*,b^*) = [s^2(L^*) + s^2(a^*) + s^2(b^*)]^{1/2} \qquad .....(4.6.10)$$

Sample Name	Y	u'	v'	L^*	a^*	b^*	$s(Y,u',v')$ $(x10^{-4})$	$s(L^*,a^*,b^*)$ $(x10^{-2})$
5R 5/12	,1833	,3527	,4934	49,91	50,96	25,89		
5R 5/12	,1832	,3529	,4937	49,90	50,94	26,09		
5R 5/12	,1830	,3530	,4939	49,87	50,92	26,15	3,32	13,85
6.25R 3/12	,0559	,4585	,5068	28,35	52,70	31,44		
6.25R 3/12	,0559	,4581	,5064	28,36	52,70	31,14		
6.25R 3/12	,0561	,4587	,5066	28,42	52,85	31,40	3,85	18,96
10R 9/2	,7619	,2113	,4688	89,98	5,18	6,40		
10R 9/2	,7569	,2115	,4691	89,75	5,19	6,65		
10R 9/2	,7666	,2110	,4682	90,20	5,17	5,94	48,79	42,48
5 YR 4/4	,1135	,2554	,5026	40,18	12,71	20,10		
5 YR 4/4	,1152	,2551	,5025	40,45	12,70	20,12		
5 YR 4/4	,1125	,2553	,5026	40,01	12,66	20,01	13,74	23,10
6.25 YR MAX	,3915	,3016	,5474	68,89	29,74	90,14		
6.25 YR MAX	,3988	,3007	,5475	69,41	29,52	90,48		
6.25 YR MAX	,3991	,3008	,5474	69,43	29,60	90,25	43,33	36,91
5Y 8.5/14	,6755	,2344	,5523	85,81	-3,84	95,21		
5Y 8.5/14	,6781	,2348	,5524	85,94	-3,61	95,65		
5Y 8.5/14	,6747	,2350	,5523	85,77	-3,48	95,29	18,06	30,89
5GY 3/4	,0572	,1871	,5246	28,72	-12,43	21,14		
5GY 3/4	,0567	,1894	,5241	28,57	-11,59	21,00		
5GY 3/4	,0564	,1866	,5251	28,50	-12,58	21,22	16,26	55,57
8.75 GY 6/12	,2756	,1451	,5560	59,51	-51,08	58,12		
8.75 GY 6/12	,2758	,1447	,5560	59,53	-51,38	58,06		
8.75 GY 6/12	,2764	,1446	,5559	59,59	-51,47	57,98	4,98	21,93
5G 6/10	,2869	,1325	,5012	60,52	-50,60	16,67		
5G 6/10	,2932	,1320	,5008	61,09	-51,22	16,52		
5G 6/10	,2914	,1324	,5002	60,93	-50,76	16,22	32,95	49,25
10G 5/10	,1916	,1156	,4846	50,90	-52,46	5,80		
10G 5/10	,1889	,1156	,4836	50,57	-52,03	5,33		
10G 5/10	,1930	,1153	,4855	51,06	-52,89	6,21	22,97	66,42
10 G 9/2	,7805	,1865	,4665	90,83	-13,03	2,63		
10 G 9/2	,7721	,1864	,4674	90,45	-13,31	3,26		
10 G 9/2	,7830	,1864	,4669	90,95	-13,25	2,94	57,28	43,59
5BG 7/8	,4184	,1448	,4645	70,79	-39,46	-1,82		
5BG 7/8	,4155	,1448	,4627	70,59	-38,99	-2,80		
5BG 7/8	,4165	,1450	,4640	70,65	-39,14	-2,07	17,46	57,20
5 B 5/8	,1917	,1388	,4053	50,91	-22,23	-25,36		
5 B 5/8	,1896	,1392	,4039	50,66	-21,60	-25,80		
5 B 5/8	,1906	,1390	,4050	50,78	-22,01	-25,44	13,00	39,64

Table 4.5 (Continued overleaf)

Sample Name	Y	u'	v'	L^*	a^*	b^*	s(Y,u',v') (x10^{-4})	s(L^*,a^*,b^*) (x10^{-2})
5 PB 3/4	,0632	,1799	,4020	30,23	1,79	-17,26		
5 PB 3/4	,0634	,1800	,4008	30,27	2,02	-17,58		
5 PB 3/4	,0642	,1797	,4028	30,46	1,58	-17,12	11,47	34,52
8.75 PB 4/12	,1137	,1907	,3457	40,21	19,80	-39,06		
8.75 PB 4/12	,1116	,1912	,3447	39,86	20,17	-39,13		
8.75 PB 4/12	,1112	,1911	,3449	39,79	20,02	-39,02	14,68	29,72
10 PB 9/2	,7529	,2007	,4556	89,56	1,71	-3,69		
10 PB 9/2	,7579	,2007	,4550	89,79	1,90	-4,08		
10 PB 9/2	,7541	,2010	,4552	89,62	1,99	-3,93	26,34	27,09
5 P 2/8	,0251	,2569	,3297	17,95	31,28	-25,64		
5 P 2/8	,0245	,2574	,3285	17,72	31,39	-25,71		
5 P 2/8	,0251	,2564	,3306	17,97	31,02	-25,49	12,17	26,23
7.5 P MAX.	,1156	,2516	,3667	40,52	39,82	-30,38		
7.5 P MAX.	,1124	,2517	,3654	40,00	39,81	-30,53		
7.5 P MAX.	,1128	,2513	,3658	40,07	39,59	-30,44	18,79	31,97
5 RP 5/10	,1835	,2934	,4411	49,94	43,02	-3,74		
5 RP 5/10	,1843	,2935	,4410	50,03	43,14	-3,79		
5 RP 5/10	,1879	,2935	,4414	50,46	43,33	-3,65	23,54	32,66
N 7.5/.	,5129	,2011	,4624	76,88	-0,27	0,89		
N 7.5/.	,5029	,2011	,4616	76,28	-0,02	0,43		
N 7.5/.	,5004	,2010	,4616	76,12	-0,05	0,41	66,30	50,14
N 2.5/.	,0433	,2003	,4613	24,75	-0,21	0,08		
N 2.5/.	,0440	,2001	,4619	24,95	-0,33	0,21		
N 2.5/.	,0439	,2003	,4615	24,93	-0,22	0,11	5,01	14,57

TABLE 4.5 : REPEATABILITY OF THE UND SPECTROPHOTOMETER

Measured data computed for Illuminant C
and rms standard deviations calculated using equations (4.6.9) and (4.6.10).

Attempts were then made to correlate these standard-deviation terms with the Munsell Hues, Values and Chromas of the test samples. Statistically significant correlations were observed in only the following two cases:

s (Y,u',v') vs Value

s (L^*,a^*, b^*) vs Value.

This is at variance with the conclusions reported in Reference [3], where there was some correlation of s with Chroma (but not with Value). This may be indicative of small nonlinearities in the UND system. The range of values of s(Y,u',v') was from 0,0003 to 0,0066 (mean 0,0023); and s(L^*,a^*,b^*) from 0,14 to 0,66 (mean 0,36). These scatter magnitudes are small enough to be insignificant in terms of ordinary colorimetric requirements; and it is clear that s(L^*,a^*,b^*) is only about one-quarter as large as ΔE(L^*,a^*,b^*).

Since s may be regarded as a measure of the repeatability of the UND system, and ΔE its accuracy, it is evident that the repeatability is of the order of ±0,5% of full scale, and the accuracy of the order of ±2% of full scale, bearing in mind that the "full-scale" value of E (L^*,a^*,b^*) is in the region of 150 CIELAB units.

However, it is probably more meaningful in the present context to consider what is the significance of a ΔE^* magnitude of some 3 CIELAB units, which was the worst-case ΔE^* between the two instruments used in these intercomparisons (Table 4.3).

It is not possible to give a general answer to this question with any degree of confidence since, as demonstrated by Robertson [19], MacAdam's ellipses of colorimetric precision [20] vary widely in shape, orientation and size over CIELAB colour space (See Chapter 2 Section 2.3.7).

Figure 6 from Robertson's paper [19] is reproduced here as Figure 4.11, and measurements on this diagram indicate that the largest ellipse has a major axis of some 45 CIELAB units and the smallest has minor axis of approximately 5 CIELAB units. Converting to radii yields values of 22,5 and 2,5 CIELAB units respectively.

Bearing in mind MacAdam's remark that the radii of his ellipses represent colour differences about 5 times greater than a just-noticeable-difference (JND) one may deduce that 1 JND is represented by anything between 0,5 and 4,5 CIELAB units (at a lightness level $L^* = 50$) depending on the location of the test colour in CIELAB space.

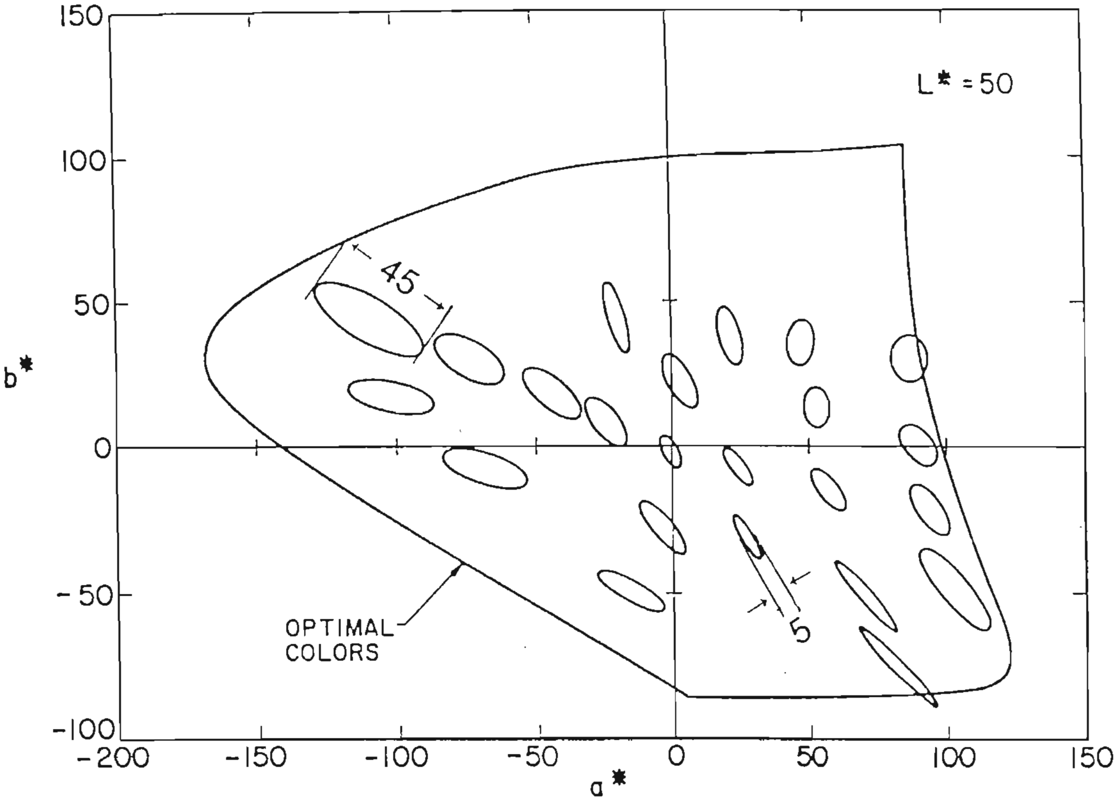

FIGURE 4.11 : MACADAM ELLIPSES TRANSFORMED TO (a,b*) COORDINATES FOR L* = 50*

The radius of any ellipse represents a colour difference equivalent to 5 JND's.

(Reproduced from Robertson [19] Figure 6.)

From this it may be deduced that the UND system has an accuracy that is roughly on a par with 1 JND in visual colorimetry, and a precision about 4 times better than this.

The values of $\Delta F(u',v')$ showed a mean of 0,0019 which would correspond roughly with a $\Delta F(x,y)$ of 0,004 in the (x,y) chromaticity diagram in the vicinity of the white point. This is only slightly larger than the target figures for repeatability set by Wharmby [21] and Jewess [22] for the measurement of near-white light sources, and can again be taken as a measure of the performance of the UND system.

4.7 SUMMARY AND CONCLUSIONS

This chapter has considered the necessity for standardized methods of colour measurements and specification in commerce and industry generally, and within the framework of the present project in particular.

Three main forms of colorimetry (visual, photoelectric, and spectrophotometric) have been examined in some detail in order to determine their relative performance characteristics and to permit a logical choice to be made of suitable colorimetric instrumentation for the purposes of this project.

Based on the findings of this study, a decision was taken to employ the spectrophotometric method of colorimetry since this appeared to offer the optimum combination of cost-effectiveness, flexibility in operation and use, and accuracy and repeatability of measured data.

Accordingly, the UND spectrophotometer system was designed, constructed and evaluated. It was found to perform within the accepted limits for industrial colorimetry, and not far outside the standards set by the National Measuring Standards laboratory.

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CHAPTER 5

EXPERIMENTAL EVALUATION OF LIGHT SOURCES FOR TELEVISION COLOUR REPRODUCTION

5.1 INTRODUCTION

This chapter describes a series of experiments [1–6] that were carried out in an attempt to assess the colour reproduction characteristics of a colour television system when taking pictures under non-standard lighting conditions.

These experiments were motivated by the fact that new types of high efficacy gas-discharge lamps are being used increasingly to illuminate areas such as sports stadiums, arenas, exhibition halls, gymnasiums and, generally, lighting areas where colour TV outside-broadcasts may be made. The high efficacy, the good optical control, and the long life of these lamps result in lighting-systems that produce more light, less heat, and a lower overall cost per lumen-hour than corresponding incandescent-lamp systems. Questions remain, however, regarding the effects that these light sources may have on the colour TV picture quality.

From the point of view of the television lighting engineer, it would be desirable to alert him to possible problems at venues lit by certain kinds of sources; while, at the same time, he needs to be made aware of the potential of some of the newer sources for possible application in studio lighting.

These experiments were independently conceived at about the same time that the CIE was beginning to concern itself with the problems of lighting for television, and they were thus not designed to form a specific part of the CIE working programme.

The CIE had, in the meantime, established a Technical Committee (initially a subcommittee) on Illumination for Colour Reproduction; and the chairman of this committee, W.N. Sproson, has in his recent book [7] given a lucid account of the assessment of illuminants for colour television, leading to the proposal for an illuminant "consistency index". Some of the details and problems of the Consistency Index methodology were surveyed by Taylor [8] who drew attention to the need for practical studio tests with different light sources in order to supplement the hitherto purely-theoretical consistency data.

The relevant CIE Technical Committee (TC1–11) has since embarked on a programme of experimental verification of the colour consistency index for practical light sources [9]. As far as can be ascertained, however, the work described in this Chapter was the first attempt to provide a valid set of comparisons of a wide selection of test lamps in a controlled experiment. It would seem to be fair to claim that, in spite of the differences in methodology, the UND data derived in these experiments does provide some measure of confirmation for the data at present available to the Committee, and has helped to mould opinion within the Committee.

Thus, although the method used in these tests does not conform in all respects with the Consistency Index approach, it is suggested that the results reported here should at least provide some additional evidence of the suitability of different light sources for use with television cameras.

The UND experiments comprised a parallel pair of investigations (one subjective and the other objective) aimed at assessing the performance of gas-discharge sources as illuminants for colour TV. In both cases, the principle of the method was to compare the colour reproductions obtained under a reference source and under each of the gas-discharge test sources in turn; i.e. a test of consistency.

Since tungsten-halogen lamps are used almost universally for TV studio lighting, and most camera systems are accordingly optimized for use with these sources, the tungsten-halogen lamp was a logical choice for the reference source in this work. Seven different varieties of HID (High Intensity Discharge) lamps were studied as test sources, along with four different types of fluorescent tubes. These latter were included on account of their possible applications in interior situations, such as sports halls and small studios. Table 5.1 contains details of the test sources investigated.

The first investigation concerned an assessment of the subjective responses of a panel of observers to changes in the illuminant, while the second was a quantitative psychophysical determination of the colour shifts that resulted from such a change.

LAMP CATEGORY	TEST SOURCE REFERENCE	LAMP DESCRIPTION
Fluorescent Tubes 1200 mm 40 W	E & H	1. High-Efficacy Warm White
	A	2. Medium-Efficacy White
	F	3. High-Efficacy White
	N	4. Trisphosphor White
High Intensity Discharge Lamps 400 W (Unless otherwise stated)	C & L	1. Coated High-Pressure-Sodium
	P	2. Phosphor-coated Mercury (early type)
	D	3. Phosphor-coated Mercury (modern type)
	B & M	4. Deluxe Phosphor-coated Mercury
	G	5. Mercury/Filament blended (500W.)
	J	6. Coated Metal-Halide (375W.)
	I	7. Tubular Metal-Halide
Reference/Studio Lamps	K	1. Tungsten-Halogen filament lamps

TABLE 5.1: TEST SOURCES INVESTIGATED

The twelve test lamps used in the TV colour reproduction investigation.

5.2 COLOUR REPRODUCTION ASSESSMENT TECHNIQUES

5.2.1 General

The need to assess either the quality or the fidelity of a colour reproduction system may arise if it is required to define the performance of the system when it is operated under either:

- optimum conditions (or standard conditions), or
- conditions that vary from the optimum (or standard) in specific respects.

In this way, it is possible to define the effects, on the quality of the reproduction, of specific variations in the operation of the system.

While colour reproduction systems differ considerably in their internal operation, they do possess certain features in common:

- Each system makes use of a camera to produce a focussed image of the scene on a photosensitive receptor within the camera.

- There is a subsequent processing stage in which the optical image information is operated on in some appropriate manner.

- Finally, the processed information can be used to reconstruct a replica of the original image for viewing on an appropriate display device.

Variations from the optimum may occur at any point within the system due to:

- Variations in the amount of light used in forming the camera image (over- or under-exposure) or in the colour quality of that light.

- Variations that may occur, either accidentally or by design, in the processing stage.

- Variations in the setting or operation of the display device, or in the ambient viewing conditions (which can lead to subjective impressions of changes in the colour of the reproduced image).

It is not always possible to correlate a specific defect in the reproduced image with a specific fault or system variation (i.e. several different factors may lead to similar results viewed subjectively on the display). However, it is possible to investigate the effects of specific system variations by ensuring that not more than one system parameter is changed, and then judging the result by observing the resultant change in the displayed image. This was the basis of the techniques used in this investigation.

The purpose of this project was specifically to assess the performance of a colour reproduction system when operated under non-standard taking illuminants – i.e. operating the camera under electric light sources that differ in their colour qualities from the standard or optimum source for which the system is specified or designed.

The methodology developed for this purpose has evolved from a technique that was originally developed to assess and compare the performance of two specific colour photographic systems, in which instance comparisons were made of their performance under a single, standard taking illuminant [10].

When the illuminant is to be varied, it has to be recognized that some form of compensation for the illuminant's colour qualities will be required. In other words, some form of colour balancing will have to be applied in the system in order to achieve a "natural looking" displayed reproduction. At first, this may appear to be an artifice that is likely to defeat the object of the investigation, but a closer consideration of the problem reveals that this step is essential if meaningful results are to be achieved. The reasoning is based essentially on the principle of colour constancy which, briefly stated, expresses the fact that human observers expect surface colours to retain their colour appearance unchanged when viewed under light sources differing markedly in spectral distribution and colour qualities. The fact that this is very largely true in a wide range of different circumstances, is evidence of the effectiveness of the chromatic adaptation properties of the human visual system.

In a purely mechanistic system this facility is lost. A good example of this is the colour reversal photographic system in which severe colour distortions are evident in pictures taken under non-standard lighting. Only with the use of appropriate filters over the camera lens, can pictures with some semblance to reality be achieved. Camera correction is thus the physical equivalent of the observer's change in chromatic adaptation when moving from one illuminant to another.

The assessment technique, therefore, has to attempt to evaluate the amount of "residual" colour shift in the reproduced scene after the system has been adjusted to simulate, as well as it is able, the chromatic adaptation process.

5.2.2 Assessment Techniques in this Project

The methods of assessment can be classified as either:

- Psychophysical (also termed Physical and Objective here), or
- Psychological (also termed Subjective here).

In the physical approach, one *measures* the relevant colours in terms of tristimulus values, chromaticity coordinates, etc, and then makes comparisons of the data to draw conclusions concerning the effects of specific changes in the system.

In the subjective approach, one makes use of a panel of observers who must attempt to quantify their own individual evaluation of the colours used in the experiment. Since such an evaluation is very difficult to carry out reliably and repeatably at an absolute level, it is normal to have the observers assess the degree of similarity or difference between colours, or their preference for the one over the other, when viewed either sequentially or simultaneously.

The remainder of this Chapter will spell out the details of the actual Subjective and Physical experiments that were carried out on a colour television system at UND, leading up to an assessment of the colour reproduction performance of twelve different lamp types.

5.3 THE SUBJECTIVE EVALUATION EXPERIMENT

A subjective scaling experiment was carried out, using a total of 23 observers, in an attempt to arrive at a scale for rating the color quality of different electric lamps as taking illuminants for a static colour television scene.

This experiment has been fully described elsewhere [1], but the following is a summary of its key features. The principles involved are illustrated in the block diagrams, Figures 5.1 and 5.2.

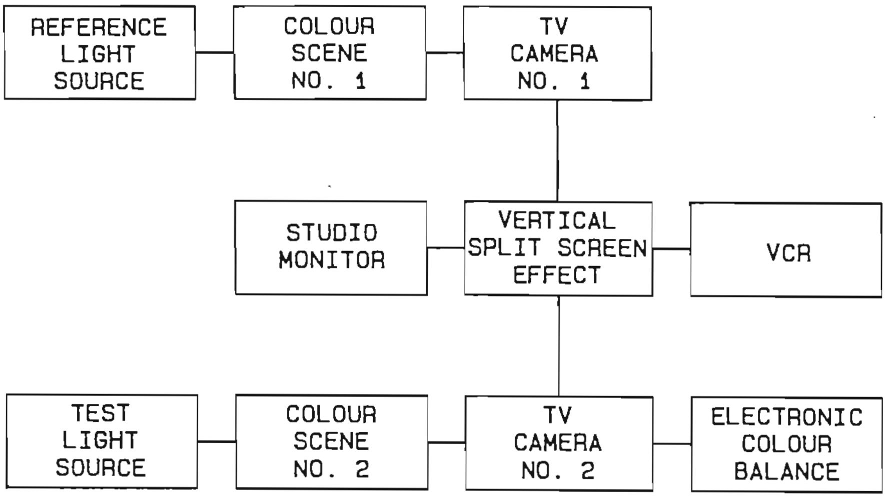


FIGURE 5.1: MAKING THE VIDEO RECORDINGS FOR THE SUBJECTIVE EXPERIMENT, USING TWO IDENTICAL COLOUR SCENES

Method of producing two side-by-side pictures of two exactly similar scenes lit by two different sources.

Details of the television cameras employed are as follows:

Camera type: Philips LDH20 with 3 plumbicons.
Plumbicon types: XQ1071 and XQ1076R (extended red sensitivity).
Lens types: Schneider variogon zoom lenses:

Camera 1:	25–112 mm f/1:1,7
Camera 2:	17–170 mm f/1:2.

Observers were required to rate their comparisons of two pictures that were presented simultaneously by means of a vertical split-screen effect on a neutral-balanced colour TV monitor. The reference-source reproduction always appeared on the right-hand side of the screen. Two test objects were used (Figures 5.3 and 5.4) the first being a commercial colour rendition chart [11], details of which are given in Table 5.2, and the second a printed portrait of a girl. The colour balance of camera No. 2 was adjusted for every test-source in order to obtain a neutral-balanced picture, with the closest possible resemblance to the reference-source reproduction. This camera adjustment was carried out by an experienced, colour-normal camera operator.

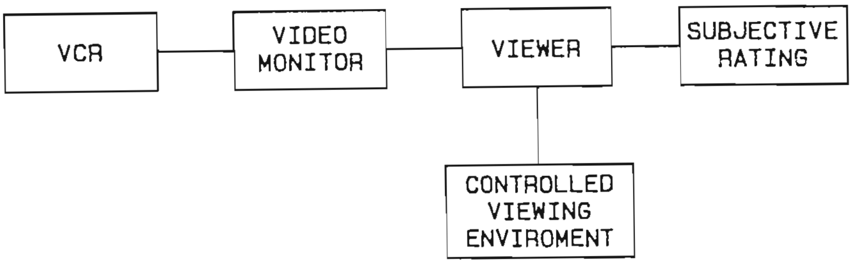


FIGURE 5.2: THE SUBJECTIVE EVALUATION SYSTEM

Playing back the video tape to members of the subjective viewing panel

Observations were carried out in a carefully controlled viewing environment and CCIR recommendations 405–2 and 500 [12,13] were followed as closely as possible within the framework of the experiment.

The test sources were presented in a random sequence, determined by lottery. Three of these sources were reintroduced randomly to assess each viewer's consistency, as well as a tungsten-halogen versus tungsten-halogen comparison to judge viewers' evaluation capability.

There was no preselection of observers in terms of their colour vision (nor any other) characteristics in this experiment, since it was felt that it was necessary to employ (as far as possible) a normal cross-section of the population in order to achieve the most realistic possible results (and a scientifically preselected group would have possessed some form of bias). It was later established that one of the 23 observers was colour deficient (evidently a severe form of anomalous trichromat) but it may be noted that his responses did not differ from the norm to any marked degree.

MANUFACTURER'S DESIGNATION		ISCC/NBS COLOUR NAME
PATCH NO.	PATCH NAME	
1	Dark Skin	Moderate Brown
2	Light Skin	Light Reddish Brown
3	Blue Sky	Moderate Blue
4	Foliage	Moderate Olive Green
5	Blue Flower	Light Violet
6	Bluish Green	Light Bluish Green
7	Orange	Strong Orange
8	Purplish Blue	Strong Purplish Blue
9	Moderate Red	Moderate Red
10	Purple	Deep Purple
11	Yellow Green	Strong Yellow Green
12	Orange Yellow	Strong Orange Yellow
13	Blue	Vivid Purplish Blue
14	Green	Strong Yellowish Green
15	Red	Strong Red
16	Yellow	Vivid Yellow
17	Magenta	Strong Reddish Purple
18	Cyan	Strong Greenish Blue
19	White	White
20	Neutral 8	Light Gray
21	Neutral 6.5	Light-medium Gray
22	Neutral 5	Medium Gray
23	Neutral 3.5	Dark Gray
24	Black	Black

TABLE 5.2: COLOUR RENDITION CHART:
COLOUR PATCH NAMES AND SPECIFICATIONS

The chart consists of a 4 by 6 array of patches, each of which is 50mm square.

FIGURE 5.3: PHOTOGRAPH OF TEST OBJECT 1

The Macbeth-Kollmorgen ColorChecker.
Approximately 50% of full size.

FIGURE 5.4: PHOTOGRAPH OF TEST OBJECT 2

An ink-printed portrait.
Approximately 50% of full size.

Ratings were assigned by observers according to two 5-point grading scales – a Comparison Scale for the first test object, and a Quality Scale for the second:

COMPARISON SCALE	
1	EQUAL
2	SLIGHTLY DIFFERENT
3	DIFFERENT
4	VERY DIFFERENT
5	EXTREMELY DIFFERENT

QUALITY SCALE	
+2	MUCH BETTER
+1	BETTER
0	EQUAL
-1	WORSE
-2	MUCH WORSE

Table 5.3 summarizes the responses of the 23 observers.

PARTICULARS

MALE	83
FEMALE	17

AGE GROUP					
11-20	21-30	31-40	41-50	51-60	Over 60
9	26	26	26	13	-

		TEST SOURCE REFERENCE														
COMPARISON SCALE		A	B	C	D	E	F	G	H	I	J	K	L	M	N	P
1	EQUAL	-	-	4	4	13	4	4	13	9	-	26	4	-	13	-
2	SLIGHTLY DIFFERENT	83	30	22	43	61	65	48	70	74	57	70	48	30	65	13
3	DIFFERENT	17	52	35	30	22	17	39	13	13	43	4	48	43	13	30
4	VERY DIFFERENT	-	17	39	17	4	13	9	4	4	-	-	-	26	9	52
5	EXTREMELY DIFFERENT	-	-	-	4	-	-	-	-	-	-	-	-	-	-	4

		TEST SOURCE REFERENCE														
QUALITY SCALE		A	B	C	D	E	F	G	H	I	J	K	L	M	N	P
+2	MUCH BETTER	-	-	-	-	4	9	9	-	-	30	22	-	-	22	-
+1	BETTER	30	17	9	17	39	-	17	61	61	43	26	4	13	70	4
0	EQUAL	9	13	4	17	13	-	-	17	17	9	17	-	-	9	-
-1	WORSE	57	65	57	65	43	35	43	22	22	17	30	26	61	-	35
-2	MUCH WORSE	4	4	30	-	-	57	30	-	-	-	4	70	26	-	61

TABLE 5.3: FREQUENCES OF RESPONSES (%)

Percentages of Group: 23 Observers.

Since each of the gradings was assigned a numerical value, it was possible to compute a mean subjective score for each test object under each test source. Table 5.4 provides a Statistical Summary (highest, lowest and mean rating, and standard deviation) for each test object under each test source. The mean values were further manipulated (using linear algebra) to yield scales covering the range 0 to 50 (approximately) with 0 signifying perfect equality and increasing values corresponding to increasing inequality (or dissatisfaction).

	TEST SOURCE REFERENCE														
COMPARISON SCALE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P
HIGHEST RATING	2	2	1	1	1	1	1	1	1	2	1	1	2	1	2
LOWEST RATING	3	4	4	5	4	4	4	4	4	3	3	3	4	4	5
MEAN RATING	2,2	2,9	3,1	2,7	2,2	2,4	2,5	2,1	2,1	2,4	1,8	2,4	3,0	2,2	3,5
STD. DEV.	0,4	0,7	0,9	1,0	0,7	0,8	0,7	0,7	0,6	0,5	0,5	0,6	0,8	0,8	0,8

	TEST SOURCE REFERENCE														
QUALITY SCALE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P
HIGHEST RATING	+1	+1	+1	+1	+2	+2	+2	+1	+1	+2	+2	+1	+1	+2	+1
LOWEST RATING	-2	-2	-2	-1	-1	-2	-2	-1	-1	-1	-2	-2	-2	0	-2
MEAN RATING	-0,3	-0,6	-1,1	-0,5	0	-1,3	-0,7	+0,4	+0,4	+0,9	+0,3	-1,6	-1,0	+1,1	-1,5
STD. DEV.	1,0	0,8	0,8	0,8	1,0	1,1	1,3	0,8	0,8	1,1	1,3	0,7	0,9	0,5	0,7

TABLE 5.4: STATISTICAL SUMMARY OF SUBJECTIVE SCALING DATA

Derived from the responses of the 28 observers.

The following transformation equations were used:

Subjective Rating (Test 1) = 10 x Mean Rating on Comparison Scale

Subjective Rating (Test 2) = 30 – (10 x Mean Rating on Quality Scale)

Statistical analysis of the two scales reveals that they correlate rather closely (Figure 5.5) and so a single figure ("Mean Subjective Rating") has been assigned to each test source. Details of the subjective ratings are given in Table 5.5.

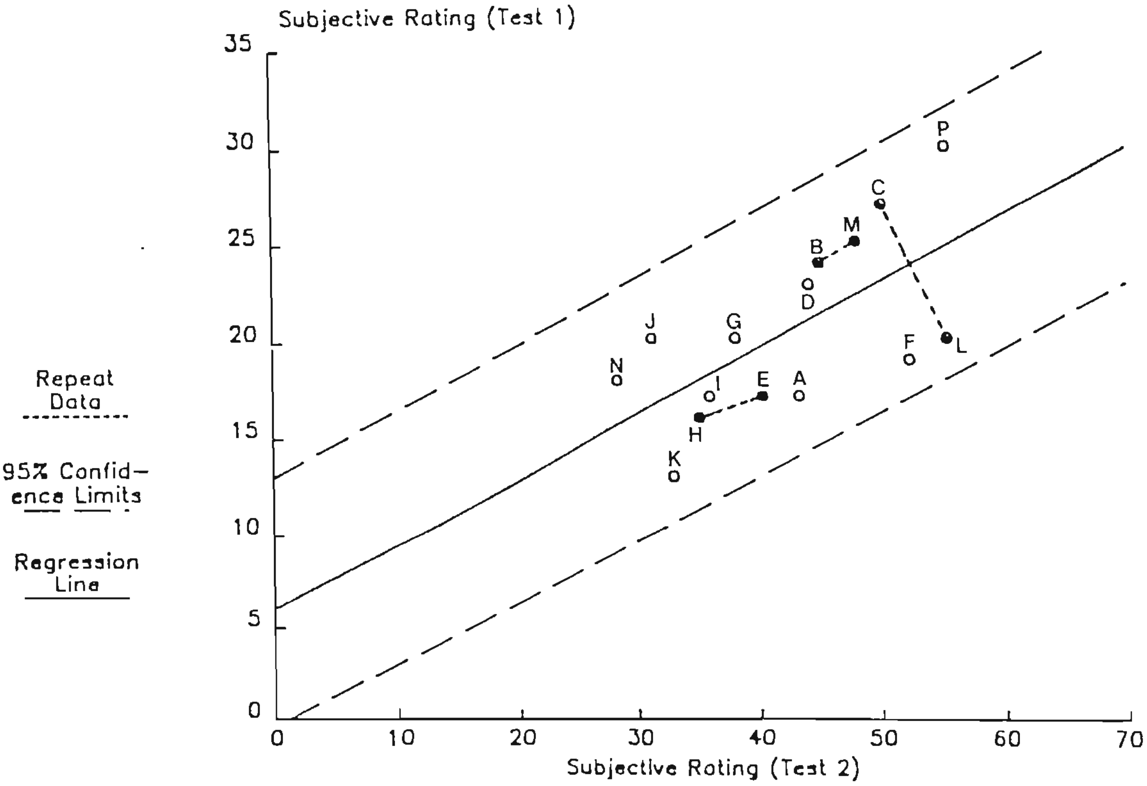


FIGURE 5.5:
RELATIONSHIP BETWEEN SUBJECTIVE RATINGS OF TESTS 1 AND 2

The two subjective scales show good correlation.

An unavoidable difficulty that arose in this experiment was an inability to obtain a perfect colour match of the images reproduced by the two colour cameras when working with the same taking illuminant. The reference scene produced by camera No. 1 was adjudged to be less pleasing than that from camera No. 2 in televising the same scene. This was discussed previously in some detail [1] and, although correction terms were estimated and incorporated into the data to compensate for this effect, the difference is not considered to be particularly significant since it appeared to correspond to a nearly constant offset in the results. It was this correction procedure that led to some of the Test 2 Ratings exceeding 50 in magnitude.

At this point, it is postulated that the MSR (Mean Subjective Rating) constitutes a meaningful measure of the TV colour-reproduction performance of each test source. What now follows is an attempt to find an objective measure that correlates sufficiently closely with the MSR for practical purposes and which will, ideally, be obtainable either by simpler or by more repeatable methods.

LAMP REFERENCE		A	B	C	D	E	F	G	H	I	J	K	L	M	N	P
SUBJECTIVE RATINGS	TEST 1	17	24	27	23	17	19	20	16	17	20	13	20	25	18	30
		4	**12**	**14**	**11**	**5**	**7**	**10**	**2**	**3**	**8**	**1**	**9**	**13**	**6**	**15**
	TEST 2	43	45	50	44	40	52	38	35	36	31	33	55	48	28	55
		8	**10**	**12**	**9**	**7**	**13**	**6**	**4**	**5**	**2**	**3**	**15**	**11**	**1**	**14**
	MEAN	30	34	39	34	29	35	29	25	26	25	23	37	37	23	42
		8	**10**	**14**	**9**	**6**	**11**	**7**	**4**	**5**	**3**	**2**	**13**	**12**	**1**	**15**

TABLE 5.5: COMPARISON OF SUBJECTIVE RANKING OF TEST LAMPS

Normal type indicates numerical values of ratings (rounded to nearest integer).

Heavy type indicates rank order within each data set.

Rank order analysis yields a coefficient of concordance W = 0,86
(significant at the 1% level).

5.4 THE OBJECTIVE EVALUATION EXPERIMENT

5.4.1 Description

A colour reproduction experiment was carried out, using the same TV system and the same lamps as before, in an attempt to arrive at some objective criterion of colour fidelity or colour consistency in the reproduced image.

The test pictures were made by use of the technique illustrated in the block diagram, Figure 5.6. The system used here is essentially the lower half of Figure 5.1, excluding the split screen effect, and the pictures were recorded at the same session at which the subjective test tapes were made. Camera No. 2 was again employed in this instance, and its colour balance was retained as set for the subjective-test recording. An enlarged image of the test chart was obtained by zooming in on the upper and lower halves of the chart in turn. This had the effect of producing reproductions of the test colour patches of about 10 cm square on the TV monitor used in the experiment.

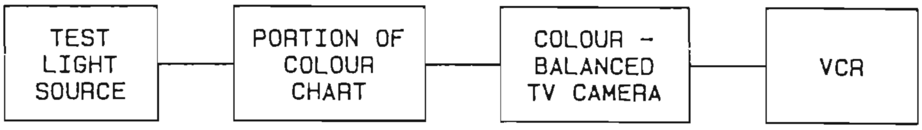


FIGURE 5.6: MAKING THE VIDEO RECORDINGS FOR THE OBJECTIVE EXPERIMENT

Retaining the camera balance as set in the previous recording (Fig.5.1).

The block diagram of Figure 5.7 illustrates the experimental setup that was used for the measurement of the test colour patches reproduced on the monitor screen. The details of the experimental procedure have been set out in an earlier paper [3] but the following is a summary of the major aspects.

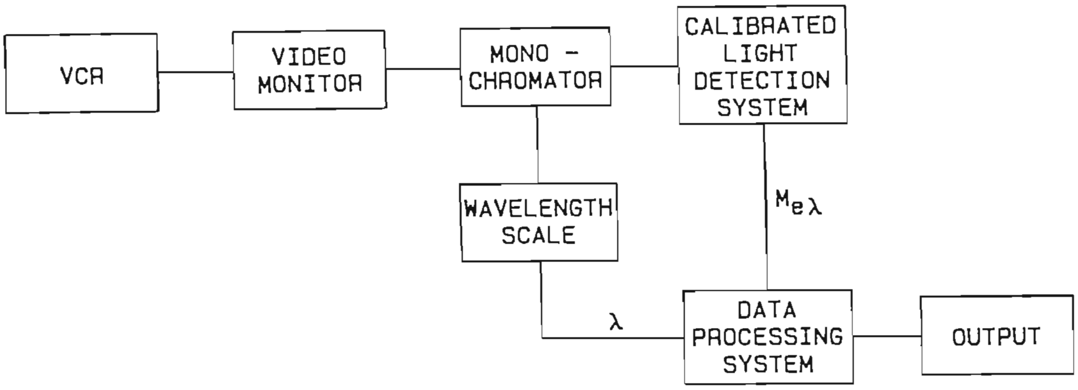


FIGURE 5.7: THE DATA ACQUISTION SYSTEM USED IN THE OBJECTIVE EXPERIMENT

The system makes use of the physical measurement of the reproduced test colour patches.

The chromaticities of the reproduced colours were to be computed from measurements of the relative spectral radiances of the respective colour patches on the monitor screen. This process is represented in Figure 5.8.

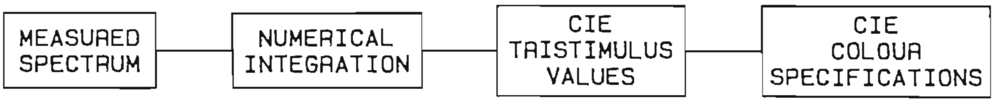


FIGURE 5.8: PROCESSING THE PSYCHOPHYSICAL DATA IN THE OBJECTIVE EXPERIMENT

The CIE Colour Specifications were computed in the forms (u',v');(L^*,u^*,v^*); (L^*,a^*,b^*).

An L-shaped "light-tunnel" was constructed to collect the light from a portion of the television screen of the required area, and to direct it to the input port of the monochromator. The angle of the "L" was fitted with a diffuse white reflecting surface at 45° to both legs of the "L". This served to integrate the screen radiance, thereby eliminating possible erroneous results that could have arisen if the monochromator were to view only a portion of the shadow mask pattern on the screen. The "light tunnel" was so positioned relative to the screen that it isolated the light flux emanating from the colour patch currently under examination, and separated it from the remainder of the screen.

Calibration of the light-detection system was achieved by the use of a tungsten-halogen spectral-radiance standard lamp, the light from which was reflected off the same white diffuser as used in the "light-tunnel". Spectral radiance measurements of the reproduced image of each colour patch, obtained under each of the test illuminants, were recorded at 10 nm intervals from 380 to 780 nm. Additional measurements were recorded at 625 and 705 nm since these wavelengths corresponded to narrowband energy peaks of the red-emitting phosphor used on the television tube (and the numerical-integration algorithm was appropriately modified to incorporate this data with the correct relative weighting).

The colour character of the reproduced image on the monitor screen is critically dependent on the settings of a number of controls on the monitor. It was therefore essential to have these controls correctly set before attempting to make any measurements of reproduced colour patches on the screen.

The CCIR recommends a peak screen luminance of 60 to 80 cd/m^2 [13]. The brightness control was thus adjusted until the white patch of the reproduced colour rendition chart registered a luminance of 70 cd/m^2.

The contrast control was next adjusted such that the decrease in luminance for each successive patch of the grey scale of the reproduced image closely matched the specified percentage decrease in luminous reflectance of the corresponding patches on the original chart.

The relative preset gains of the Red–, Green–, and Blue-channel amplifiers were then adjusted to yield a visual colour match between the white patch of the colour rendition chart and Illuminant C as synthesised on the visual colorimeter (using Illuminant C as the reference white in this experiment).

Finally, the saturation control was set using the "light skin" colour patch as the standard, this being regarded as the most critical of the colours in a reproduction. The saturation was adjusted until the colour patch image on the screen matched as closely as possible the "light skin" colour which was again synthesised on the visual colorimeter. Once these settings were complete, it was possible to proceed with the measurements of the reproduced colours on the monitor screen.

Measurements were made of the SPD's of the reproduced images of the individual colour patches of the colour rendition chart. Similar images were measured for each of the selected test sources as well as the reference source. Because of the volume of data to be collected, this experiment was limited to a subset comprising 8 of the original 12 test sources.

The following colour differences and chromaticity differences were computed from the measured SPD's:

(i) differences between the original test chart (under illuminant C) and each of the reproduced images; and

(ii) differences between the reference reproduction and each of the other reproductions.

In each instance, the differences were averaged for all the colour patches (excluding neutrals) reproduced under one source, and the resultant values rescaled using linear algebra to cover the range 0 to 50 (approximately) with 0 signifying perfect equality and increasing values corresponding to increasing differences. The data set obtained by method (i) can be regarded as a measure of "colour fidelity" (which was included for the sake of completeness, although not a primary aim of the work); while method (ii) yields a measure of colour consistency.

Various forms of colour difference equation were used in both instances, as defined below for the ith test colour patch ($i = 1,2,....18$) and the jth test source ($j = 1,2,....8$).

5.4.2 Definition of Terms (Refer also to Figure 5.9)

(a).Original Test Colours

The ith colour patch on the test chart possesses CIE tristimulus values:

$(X_{oic}, Y_{oic}, Z_{oic})$

when illuminated by CIE illuminant C.

Under the same conditions, the nominally-white colour patch on the same chart possesses tristimulus values:

$(X_{onc}, Y_{onc}, Z_{onc})$.

From these may be derived, by the use of standard CIE transformation equations, the data for the ith colour patch:

(i) the CIE 1976 chromaticity coordinates (u'_{oic}, v'_{oic});

(ii) the sets of CIE 1976 psychometric coordinates $(L^*_{oic}, a^*_{oic}, b^*_{oic})$ and $(L^*_{oic}, u^*_{oic}, v^*_{oic})$.

(b).Reproduced Test Colours (Reference Source q)

Using the Reference Source as the taking illuminant, the reproductions on the colour TV monitor of the ith colour patch and the nominally-white colour patch respectively possess tristimulus values:

$(X_{riq}, Y_{riq}, Z_{riq})$ and $(X_{rnq}, Y_{rnq}, Z_{rnq})$.

From these may be derived:

(u'_{riq}, v'_{riq}); $(L^*_{riq}, a^*_{riq}, b^*_{riq})$ and $(L^*_{riq}, u^*_{riq}, v^*_{riq})$.

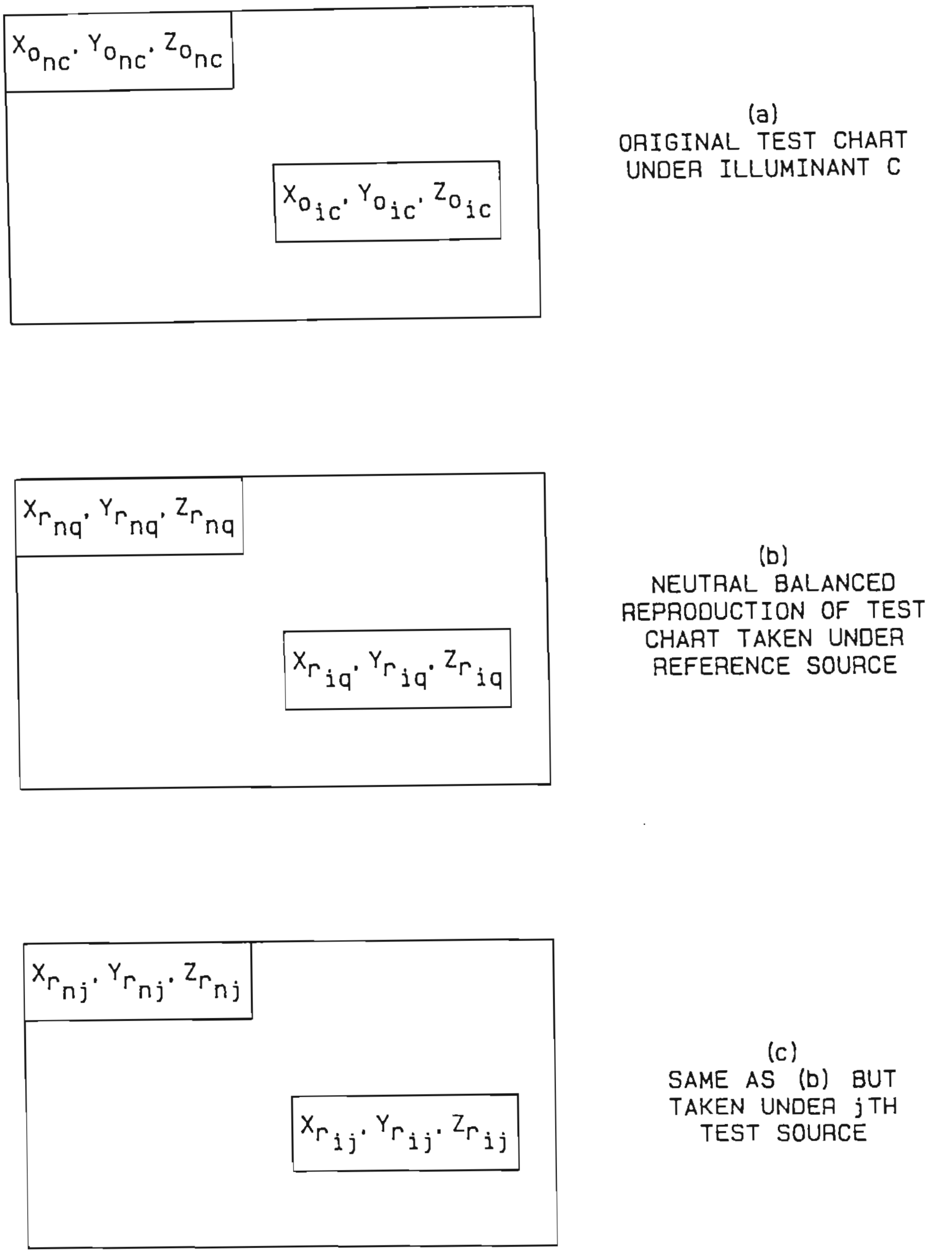
(c).Reproduced Test Colours (Test Source j)

The reproductions on the colour TV monitor of the ith colour patch and the nominally-white colour patch (both taken using the jth test source) respectively possess tristimulus values:

$(X_{rij}, Y_{rij}, Z_{rij})$ and $(X_{rnj}, Y_{rnj}, Z_{rnj})$.

From these may be derived:

(u'_{rij}, v'_{rij}); $(L^*_{rij}, a^*_{rij}, b^*_{rij})$ and $(L^*_{rij}, u^*_{rij}, v^*_{rij})$.



(a)
ORIGINAL TEST CHART
UNDER ILLUMINANT C

(b)
NEUTRAL BALANCED
REPRODUCTION OF TEST
CHART TAKEN UNDER
REFERENCE SOURCE

(c)
SAME AS (b) BUT
TAKEN UNDER jTH
TEST SOURCE

FIGURE 5.9: DEFINITIONS OF TERMS USED IN THE OBJECTIVE EVALUATION OF COLOUR FIDELITY AND COLOUR CONSISTENCY

Each colour patch is represented by its tristimulus values and their subscripts according to the following system: T_{123}
where $T =$ *the tristimulus value* (X *or* Y *or* Z)
Subscript 1 = o(original) or r(reproduction)
Subscript 2 $= i =$ *number of the colour patch*
(= n for the nominally white colour patch)
Subscript 3 $= j =$ *number of the test source*

5.4.3 Colour Difference Equations

Method (1): Measures of Colour Fidelity

The differences assessed here are between each reproduced colour patch and its "original" appearance on the test chart under Illuminant C.

The CIE–1976 Chromaticity difference was scaled by a factor of 1000 to yield:

$$1000\Delta F_{1ij} = 1000\,[\,(u'_{rij} - u'_{oic})^2 + (v'_{rij} - v'_{oic})^2]^{1/2} \quad .....(5.4.1)$$

The CIE–1976 colour differences were calculated without additional scaling:

$$\Delta E^*_{1ij}(Luv) = [\,(L^*_{rij} - L^*_{oic})^2 + (u^*_{rij} - u^*_{oic})^2 + (v^*_{rij} - v^*_{oic})^2]^{1/2} \quad .....(5.4.2)$$

$$\Delta E^*_{1ij}(Lab) = [\,(L^*_{rij} - L^*_{oic})^2 + (a^*_{rij} - a^*_{oic})^2 + (b^*_{rij} - b^*_{oic})^2]^{1/2} \quad .....(5.4.3)$$

Each of these quantities was averaged for the 18 test colours (reproduced using test source j) to yield what one may designate as "Objective Ratings" for that source:

$$1000\,\overline{\Delta F}_{1j} = (1/18)\sum_{i=1}^{18} 1000\,\Delta F_{1ij} \quad .....(5.4.4)$$

$$\overline{\Delta E}^*_{1j}(Luv) = (1/18)\sum_{i=1}^{18} \Delta E^*_{1ij}(Luv) \quad .....(5.4.5)$$

$$\overline{\Delta E}^*_{1j}(Lab) = (1/18)\sum_{i=1}^{18} \Delta E^*_{1ij}(Lab) \quad .....(5.4.6)$$

Method (2): Measures of Colour Consistency

The differences assessed here are between each reproduced colour patch as "taken" under source j and the corresponding reproduction "taken" under the tungsten-halogen reference source q.

The CIE–1976 chromaticity difference was scaled by a factor of 1000 to yield:

$$1000\Delta F_{2ij} = 1000\,[\,(u'_{rij} - u'_{riq})^2 + (v'_{rij} - v'_{riq})^2]^{1/2} \quad .....(5.4.7)$$

The CIE-1976 colour differences were calculated without additional scaling:

$$\Delta E^*_{2ij}(Luv) = [\,(L^*_{rij} - L^*_{riq})^2 + (u^*_{rij} - u^*_{riq})^2 + (v^*_{rij} - v^*_{riq})^2]^{1/2} \qquad .....(5.4.8)$$

$$\Delta E^*_{2ij}(Lab) = [\,(L^*_{rij} - L^*_{riq})^2 + (a^*_{rij} - a^*_{riq})^2 + (b^*_{rij} - b^*_{riq})^2]^{1/2} \qquad .....(5.4.9)$$

A colour difference equation with a reduced weighting for ΔL^* has been suggested by De Marsh [14] hence the use of the symbology $\Delta E^*_2(DM)$:

$$\Delta E^*_{2ij}(DM) = [\,1/4(L^*_{rij} - L^*_{riq})^2 + (u^*_{rij} - u^*_{riq})^2 + (v^*_{rij} - v^*_{riq})^2]^{1/2} \qquad .....(5.4.10)$$

The 18 colour differences computed for each test source j are averaged to yield what may be regarded as "Objective Ratings of Colour Consistency" for that source:

$$1000\,\overline{\Delta F}_{2j} = (1/18) \sum_{i=1}^{18} 1000\,\Delta F_{2ij} \qquad .....(5.4.11)$$

$$\overline{\Delta E}^*_{2j}(Luv) = (1/18) \sum_{i=1}^{18} \Delta E^*_{2ij}(Luv) \qquad .....(5.4.12)$$

$$\overline{\Delta E}^*_{2j}(Lab) = (1/18) \sum_{i=1}^{18} \Delta E^*_{2ij}(Lab) \qquad .....(5.4.13)$$

$$\overline{\Delta E}^*_{2j}(DM) = (1/18) \sum_{i=1}^{18} \Delta E^*_{2ij}(DM) \qquad .....(5.4.14)$$

5.4.4 Summary of Findings

The aim here was to find a colour difference equation that yielded an Objective Rating having the best correlation with the MSR obtained in the subjective evaluation experiment. The values of the measured Objective Ratings are listed in Table 5.6. Linear regression of each of the objective ratings respectively against the MSR yielded the findings summarized in Table 5.7.

TEST SOURCE REFERENCE	MEAN SUBJECTIVE RATING	MEASURED OBJECTIVE RATINGS						
		$1000\overline{\Delta F}_1$	$\overline{\Delta E^*}_1$ (Luv)	$\overline{\Delta E^*}_1$ (Lab)	$1000\overline{\Delta F}_2$	$\overline{\Delta E^*}_2$ (Luv)	$\overline{\Delta E^*}_2$ (Lab)	$\overline{\Delta E^*}_2$ (DM)
A	30	55	43	31	45	42	31	41
C	39	39	32	26	42	30	23	27
E	29	66	59	39	56	56	39	54
F	35	52	39	25	44	37	25	35
I	26	46	33	25	26	29	22	26
J	25	59	37	28	33	31	22	29
K	23	35) 27) 31*	29) 27) 28*	24) 19) 21*	0	0	0	0
N	23	36	28	23	30	30	24	27

TABLE 5.6:
SUBJECTIVE AND OBJECTIVE RATINGS OF TV SYSTEM PERFORMANCE WITH EIGHT DIFFERENT TAKING ILLUMINANTS

Each of the numerical ratings has been rounded to the nearest integer.
**Lamp K (Reference Source): Measured twice: Mean data used in regression analysis.*

OBJECTIVE RATING	REGRESSION COEFFICIENTS		CORRELATION COEFFICIENT	EST. SIGNIFICANCE LEVEL WITH 6 DEGREES OF FREEDOM
	a_o	a_1	r	
$1000\overline{\Delta F}_1$	38,52	+0,33	+0,16	80%
$\overline{\Delta E}_1$ *(Luv)	26,45	+0,38	+0,22	60%
$\overline{\Delta E}_1$ *(Lab)	21,77	+0,19	+0,20	80%
$1000\overline{\Delta F}_2$	-15,74	+1,75	+0,60	20%
$\overline{\Delta E}_2$ *(Luv)	2,72	+1,01	+0,37	40%
$\overline{\Delta E}_2$ *(Lab)	3,61	+0,68	+0,36	40%
$\overline{\Delta E}_2$ *(DM)	2,20	+0,96	+0,36	40%

TABLE 5.7: LINEAR REGRESSION OF OBJECTIVE RATINGS AGAINST MSR

Equation of regression line : $y = a_0 + a_1 x$
Here y represents the Objective Rating and x the MSR.

It is clear from Table 5.7 that none of the objective ratings of colour fidelity (subscript 1) yielded a significant correlation with the MSR, and the majority of the ratings of colour consistency (subscript 2) are only marginally better. However, the mean-chromaticity-difference rating $1000\overline{\Delta F}_2$ does provide a correlation with the MSR that can be regarded as moderately significant.

It is perhaps also of interest to note that all seven objective ratings listed in Table 5.7 did possess positive values of the coefficients a_1 and r indicating a positive trend in all attempted correlations.

Figure 5.10 shows a plot of $1000\overline{\Delta F}_2$ against the MSR for the eight light sources employed in this test, and also includes the regression line and 95% confidence limits.

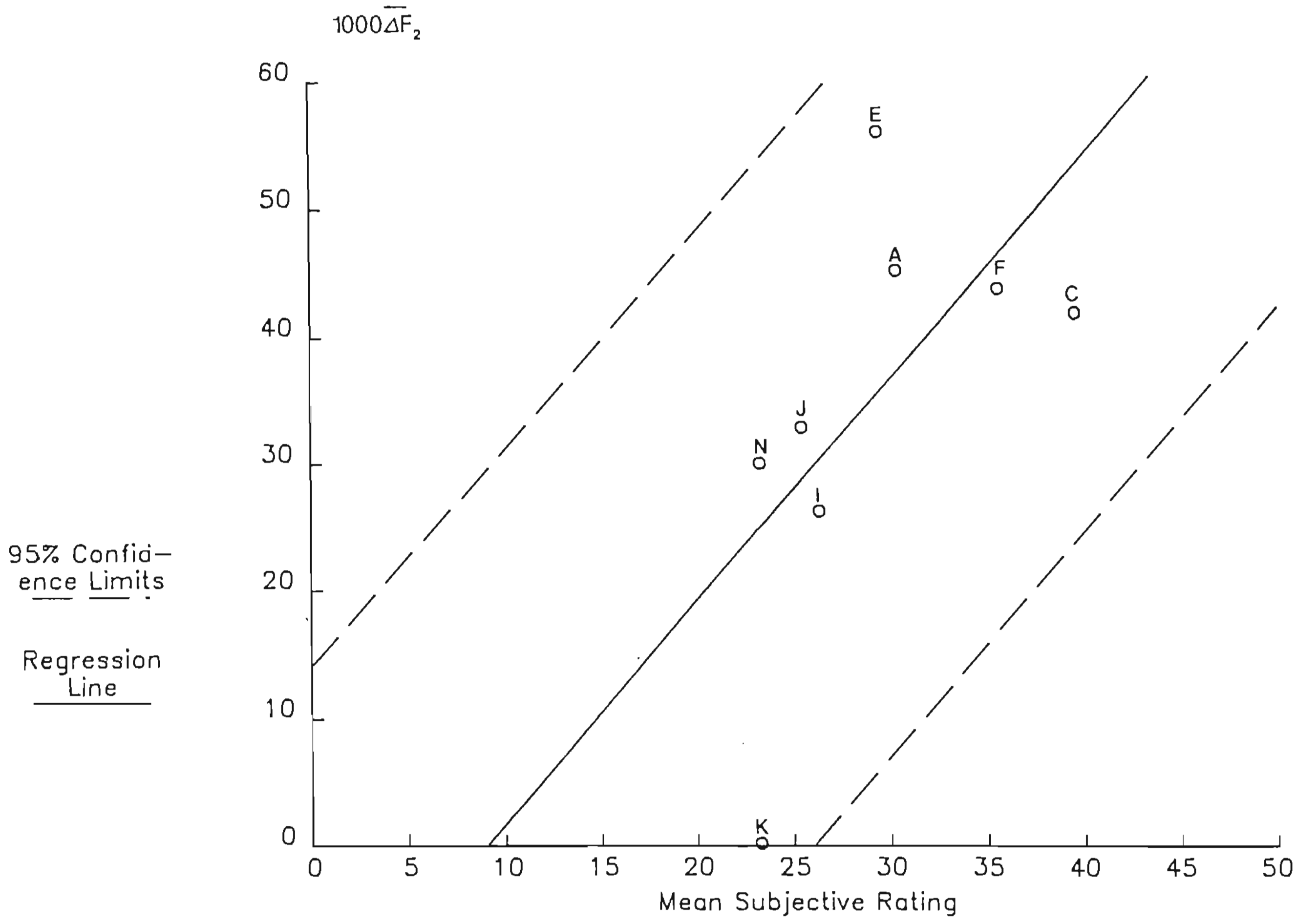


FIGURE 5.10: CORRELATION OF OBJECTIVE WITH SUBJECTIVE CONSISTENCY DATA

There is little correlation of the chromaticity difference (objective rating) with the MSR.

5.5 ALTERNATIVE MEASURES OF LIGHTING QUALITY

The correlation achieved between $1000\overline{\Delta F}_2$ and MSR was not particularly satisfactory, and other measures of lamp performance were therefore considered for investigation. Of these, the most obvious candidate is the CIE colour rendering index R_a, and it was accordingly decided to investigate the possible correlation between nominal R_a values (obtained form the lamp manufacturers) and the MSR obtained in the first part of this experiment. The relevant values for the test lamps are quoted in Table 5.8, along with a new quantity D_a defined by

$$D_a = 100 - R_a$$

and it is this quantity that was plotted against the MSR in Figure 5.11. Also shown is the regression line of D_a on MSR, together with its 95% confidence limits. The correlation coefficient in this instance was r = 0,74 which is highly significant (at the 1% level, with 13 degrees of freedom).

LAMP REFERENCE	A	B/M	C/L	D	E/H	F	G	I	J	K	N	P
NOMINAL CIE R_a	75	52	25	45	52	66	50	68	68	100	85	45
NOMINAL DEMERIT D_a	25	48	75	55	48	34	50	32	32	0	15	55

TABLE 5.8: LAMP COLOUR RENDERING DATA

Nominal data quoted by the lamp manufacturers.

The reason for choosing to plot D_a (rather than R_a) against MSR in Figure 5.11 was that D_a has a similar significance to MSR, in that both quantities are measures of the degree of *imperfection* of the light sources, and they should therefore possess a positive correlation (as was indeed found to be the case).

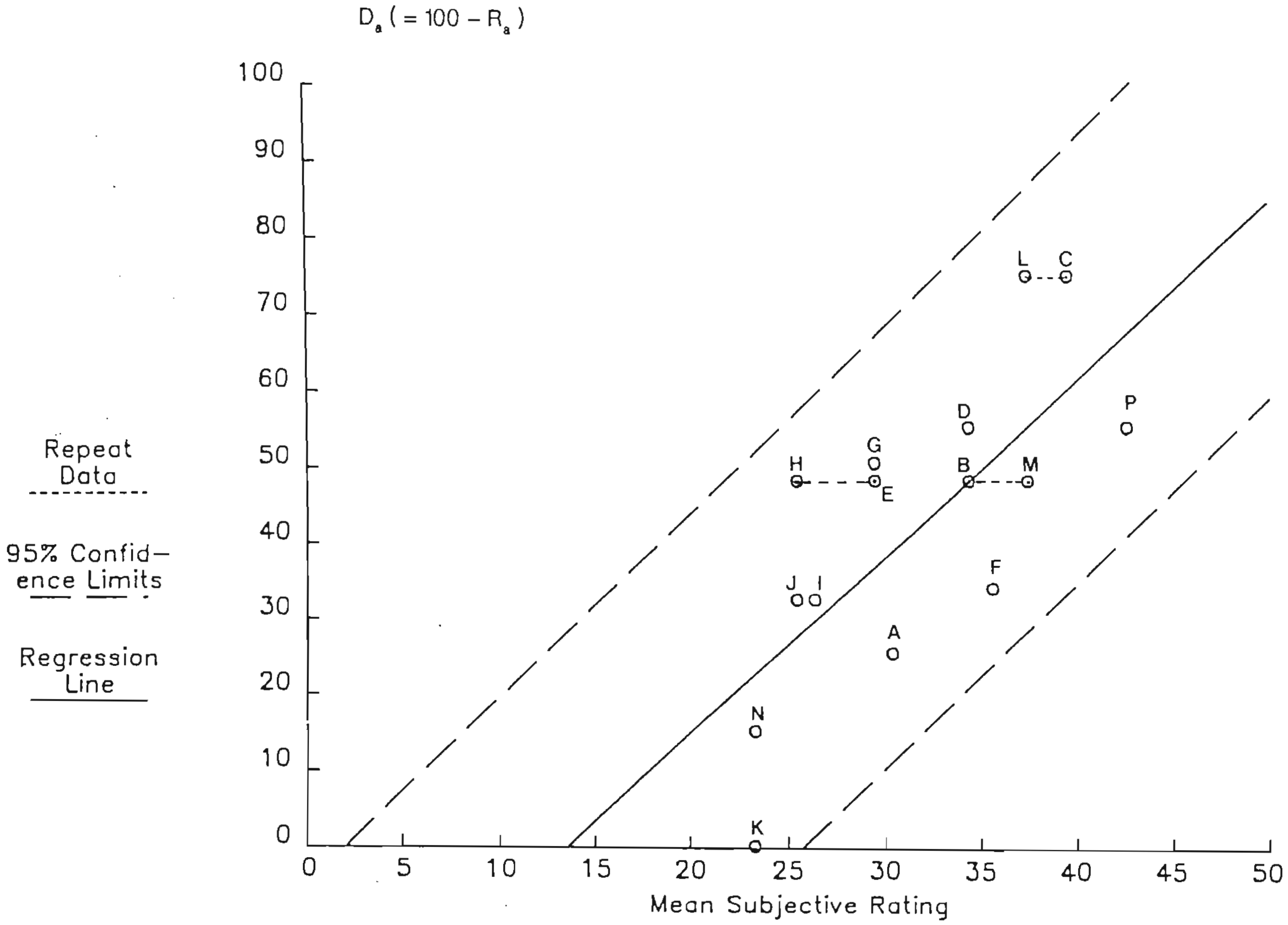


FIGURE 5.11:
CORRELATION OF NOMINAL CRI WITH SUBJECTIVE DATA

There is good correlation betweeen D_a and the MSR.

5.6 ASSESSMENT OF THE INDIVIDUAL TEST COLOURS

As mentioned in Section 5.4 above, there was a small to moderate degree of correlation between the various objective ratings and the mean subjective rating. Now, it has to be borne in mind that each of these objective ratings was obtained as the mean of 18 colour differences, and that the averaging process could well have been masking interesting effects with individual colours. It will thus be recognized that there could possibly exist, within the arrays of colour difference data, some colour difference quantity (say ΔF_{Nij}) which shows a more significant correlation (than did $1000\Delta F_{2j}$) with the MSR.

Because of the volume of data to be analysed (1008 points), a preliminary screening process was adopted, employing rank order analysis. This involved the rank order correlation of the MSR data set with each of the 126 other data sets in turn (each set comprising 8 colour difference values) and the computation of Kendall's coefficient of concordance W, together with the value of chi-square as a test of community of preference, for each pair. Table 5.9 lists those data sets having significant rank-order similarity to the MSR. In order to keep the table reasonably concise, it has been limited to those cases yielding chi-square values higher than 10 (i.e. approximately the 20% significance level with 7 degrees of freedom) obtained in the colour consistency experiment (Method (2) above).

On the strength of this information, it was decided to proceed with the regression analysis of the 18 sets of chromaticity differences expressed as $1000\Delta F_2$ against the MSR. The results of this analysis are summarized in Table 5.10, and the two most significant correlations – those for the magenta and yellow samples – are illustrated in Figure 5.12.

TEST SOURCE REFERENCE	MSR RANKING	$1000\Delta F_2$ RANKINGS					ΔE^*_2(Luv) RANKINGS			ΔE^*_2(Lab) RANKINGS				ΔE^*_2(DM) RANKINGS		
		COLOUR PATCHES					COLOUR PATCHES			COLOUR PATCHES				COLOUR PATCHES		
		BLUE SKY	BLUISH GREEN	ORANGE	YELLOW	MAGENTA	DARK SKIN	ORANGE	YELLOW GREEN	DARK SKIN	ORANGE	YELLOW GREEN	YELLOW	DARK SKIN	ORANGE	YELLOW GREEN
A	6	6	8	2	4	5	3	5	6	4	5	7	6	3	4	6
C	8	3	4	8	8	8	8	8	5	8	8	4	5	8	8	5
E	5	8	7	5	6	7	4	7	7	6	7	6	8	5	7	7
F	7	7	6	7	7	6	7	6	8	7	6	8	7	7	6	8
I	4	5	2	6	2	3	4	4	2	5	4	2	2	4	5	2
J	3	4	5	4	3	4	6	3	3	3	2	3	3	6	3	4
K	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
N	1	2	3	3	4	2	2	2	3	2	3	5	3	2	2	3
Coefficient of Concordance W with MSR ranking		0,74	0,74	0,82	0,75	0,91	0,74	0,92	0,75	0,92	0,90	0,73	0,73	0,85	0,90	0,83
Chi-Square		10,4	10,4	11,4	10,5	12,8	10,3	12,9	10,5	12,9	12,6	10,3	10,2	11,9	12,6	11,6
Significance Level		20%	20%	15%	20%	10%	20%	10%	20%	10%	10%	20%	20%	15%	10%	15%

TABLE 5.9:
RANK ORDER CORRELATIONS OF OBJECTIVE RATINGS WITH MSR:
INDIVIDUAL COLOUR PATCHES

Assessing the extent to which the rank order for measured colour consistency of individual colour patches agreed with the MSR.

TEST COLOUR NAME	REGRESSION COEFFICIENTS		CORRELATION COEFFICIENT	EST. SIGNIFICANCE LEVEL WITH 6 DEGREES OF FREEDOM
	a_o	a_1	r	
MAGENTA	-203,0	+9,76	+0,87	1%
YELLOW	-20,1	+1,35	+0,80	2%
ORANGE	-44,2	+2,55	+0,76	5%
BLUISH GREEN	-12,5	+1,21	+0,48	30%
DARK SKIN	-26,8	+3,17	+0,39	40%
LIGHT SKIN	1,07	+0,60	+0,30	50%
CYAN	-6,03	+1,15	+0,30	50%
ORANGE YELLOW	-2,90	+0,50	+0,30	50%
YELLOW GREEN	4,75	+0,35	+0,30	50%
BLUE SKY	-7,70	+1,42	+0,27	WORSE THAN 50%
MODERATE RED	7,37	+0,63	+0,24	" " 50%
RED	6,63	+0,37	+0,22	" " 50%
BLUE	9,26	+0,81	+0,21	" " 50%
FOLIAGE	28,2	+0,94	+0,19	" " 50%
PURPLISH BLUE	9,31	+0,57	+0,16	" " 50%
GREEN	15,1	+0,31	+0,15	" " 50%
PURPLE	45,4	+0,72	+0,09	" " 50%
BLUE FLOWER	30,1	+0,27	+0,05	" " 50%

TABLE 5.10: LINEAR REGRESSION OF 1000ΔF_2 AGAINST MSR

a_0 and a_1 are as defined for Table 5.7.

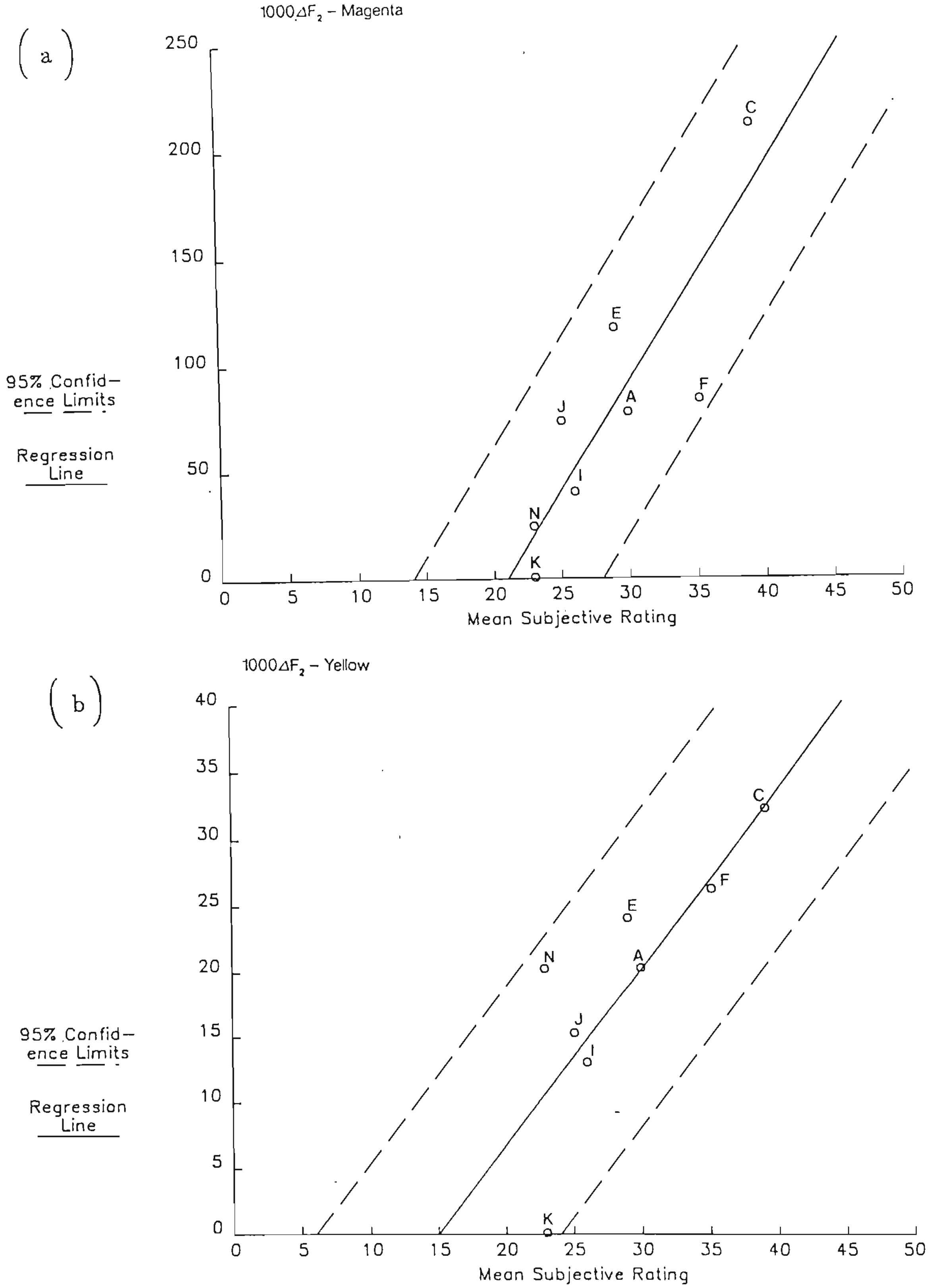


FIGURE 5.12: CORRELATION OF OBJECTIVE AND SUBJECTIVE DATA FOR SPECIFIC TEST COLOURS: (a) Magenta (b) Yellow

These two samples showed the highest correlation between the objective and subjective tests for lamp performance in respect of colour reproduction consistency.

5.7 EVALUATION OF RESULTS

It is believed that a consistent subjective measure has been established for the colour reproduction performance of a television system operated with a variety of different scene illuminants. This measure has been termed the MSR. Since it is based on the average of the responses of 23 observers, it can be considered to constitute a representative measure.

Pairs of points have been plotted in Figures 5.5 and 5.11 for lamps B, C and E, these being the test sources that were reintroduced (as sources M, L and H) to monitor observer-consistency. It will be noted that the separation of each pair is noticeably less than the width of the 95% confidence band, and so it can be concluded that the observers were, as a group, highly consistent in their subjective evaluation of the test reproductions.

The MSR has been shown to correlate closely with the quantity D_a (and hence also with R_a, the CIE colour rendering index of each test source) and, less closely, with the measured quantity $1000\overline{\Delta F}_2$ (the mean chromaticity difference measured on the actual TV system employed in this experiment) which is a measure of colour consistency.

Contrary to the interim findings published earlier [3], no useful correlation was found to exist when assessing consistency using colour difference formulas based on the CIE 1976 (L^*, u^*, v^*) or (L^*, a^*, b^*) colour spaces. Nor was there any useful correlation when colour differences were calculated with reference to the original sample colours as an attempt at defining the colour fidelity of the system. It is necessary to bear in mind, however, that these findings may well be a result of the specific choice of test colours, and of the experimental technique employed.

Table 5.10 shows that only half of the 18 test colours yielded even marginally acceptable degrees of correlation between $1000\Delta F_2$ and MSR (with significance levels 50% or better) although the correlation remained positive in all cases. If these 9 colours only were to be used in estimating a new objective rating measure, say $1000\overline{\Delta F}_2'$, it is highly probable that $1000\overline{\Delta F}_2'$ would correlate more closely with MSR than does the $1000\overline{\Delta F}_2$ computed here. It is clearly also possible to apply this process of reasoning to the objective ratings based on the CIELUV and CIELAB formulas, and so the fundamental importance of the choice of test colours becomes obvious.

Further evidence of this is provided by the fact that two of the test colours that appear in Table 5.9 under the three DE_2^* headings (viz. Dark Skin and Yellow Green) do not feature among the five test colours listed under $1000\Delta F_2$ in the same table.

In view of the importance of skin colour in assessing the performance of colour reproduction systems it may, at first sight, seem surprising that the Dark Skin and Light Skin test colour patches feature only in 5th and 6th places in Table 5.10. It is thought that this is most likely due to the rebalancing of colour camera No. 2 for each test source at the recording stage (as already explained in Sections 5.2 and 5.3) since the camera operator would have been paying greatest attention to the neutrals and the skin colours in the test scene, in attempting to optimize the match between the two halves of the split-screen picture (see also Figure 5.1). Perhaps even more significant, in the case of the measurements used in the objective ratings, was the balancing of the monitor using "light skin" as one of the "target" colours (Section 5.4.1). The operator's random errors are, therefore, probably responsible for much of the randomness present in these two cases.

Another surprising feature contained in Table 5.10 is the highly significant correlation of $1000\Delta F_2$ with MSR for the Magenta test colour sample. This is not a colour that one normally thinks of as critical in most colour reproduction work and its high significance in this data set is probably a consequence of the side-by-side comparisons in the split-screen technique used in this experiment. It should also be borne in mind that the second test object in the subjective experiment was a printed portrait of a girl. This picture contained several highly saturated splashes of colour (one of which was magenta) and these would certainly have had an important influence on observer reaction as estimated by the MSR.

Summarizing, then, it seems that, apart from the well-established (and inefficient) tungsten-halogen lamp, the light sources that appear to possess the greatest potential for use in TV colour reproduction are:

(i) the "triphosphor" type fluorescent tube, and
(ii) the metal-halide type high-intensity discharge lamp.

Some of the important engineering features of these sources are summarized in Table 5.11.

It has to be borne in mind that fluorescent tubes are traditionally used in situations where an area is to be more-or-less uniformly lit in a relatively diffuse manner. Their low luminance and large size are not likely to be readily accepted by television production staff who tend to make greater use of small high-intensity sources whose output can more readily be directed or focussed to achieve the necessary accents and contrasts in the TV picture. Fluorescent luminaires with directional light-output properties are now available, however, at fairly moderate cost, and it is suggested that fluorescent tubes should not be rejected out of hand for TV lighting.

CHARACTERISTICS	TUNGSTEN-HALOGEN LAMP	TRIPHOSPHOR FLUORESCENT TUBE	METAL-HALIDE HID LAMPS
CIE R_a (Typical)	100	85	65-80
Lamp Efficacy (lm/W -typical)	20	75	80
Circuit Efficacy (lm/W -estimated)	20	65	70
Heat loss per klm of lamp flux (W)	50	16	14
Typical Lamp Life (hours)	2000	7500	1000 upwards
Lamp Size	Small/Medium	Medium/Large	Small/Medium
Ease/efficiency of optical control	Moderate/Good	Moderate/Poor	Moderate/Good
Ease/efficiency of electrical control	Simple	Moderate	Complex
Stability of colour properties over lamp life	Good	Not established	Variable in some types

TABLE 5.11: SOME TYPICAL LAMP PROPERTIES

Some performance features of the more promising types of lamps.

The information given in Table 5.11 can be used to draw economic comparisons between the different lamps. Such comparisons can usually only be exact for specific situations, but some general remarks on the relative economic merits of the above three lamp types would not be entirely out of place.

To begin with, it must be borne in mind that the annual cost of ownership of any piece of equipment can be determined from the sum of the annual running costs and the annual amortisation on the capital outlay.

It is often the case, in making cost comparisons of different lighting systems, that cheap systems (in terms of capital cost) are expensive to run, and vice-versa. However, the capital cost should incorporate the cost of providing electric power to the lighting system, plus the cost of cooling the installation if it is an interior space. E.g. the air conditioning load in a conventionally-lit TV studio is far from negligible.

The following list gives an indication of the factors that will contribute to a *lowering* of each of the components of the cost of ownership of a TV lighting system:

RUNNING COSTS
–High Lamp Efficacy
–Long Lamp Life
–Ease of Lamp Replacement
–Low Lamp Cost

CAPITAL COSTS

–High Lamp Efficacy
–Efficient Luminaire Optics
–Low Luminaire Cost
–Long Luminaire Life

A high lamp efficacy contributes significantly to lowering the capital costs by reducing both the power supply and the air conditioning requirements. With respect to running costs, it contributes to a lower energy consumption charge.

Amortisation costs will, of course, be determined by prevailing financial circumstances (specifically, interest rates) and policy; while energy costs will be determined by the prevailing tariffs and the method of metering.

In spite of all the undefined factors in the cost equation, however, there would seem to be a good case to be made for the gas-discharge lamps with their relatively high efficacies.

5.8 DISCUSSION

Several criticisms may be levelled against this experiment and the conclusions drawn from it. The following are probably the most important of these:

(i).the test scenes were static, and do not therefore constitute a real test of a television system;

(ii).there has been criticism of the commercial test chart that was used in this work;

(iii).only a single set of lamps has been assessed, comprising only one sample of each type of HID test lamp, and a fixed set of four tubes in the case of each type of fluorescent test lamp;

(iv).only one TV system has been assessed;
(v).a relatively small group of observers was used for the subjective evaluations;

(vi).the vertical split-screen method (i.e. the presentation of the test pictures alongside the reference picture) is regarded as unduly exacting.

All of these remarks are perfectly true, and point to the need for care in drawing general conclusions from this work. It is hoped that the following discussion will show, however, that they do not invalidate the conclusions previously drawn.

Static test scenes, it is true, are not necessarily the best way of testing a TV system. However, since the conclusions are based on a comparison of the test and reference scenes, it was necessary to have two identical test objects to be reproduced side-by-side on the monitor screen. (Satisfactory reproduction of moving objects may have called for higher illuminance levels in order to avoid camera lag, but this aspect has been dealt with elsewhere [15,16]).

The commercial *colour rendition test chart* that was used in this work has come under criticism for a lack of quality control and inexact spectral reflectances of the test colours [17]. Since the two charts that were actually used in this work were found to be closely similar, this criticism does not invalidate the major conclusions which were based on comparisons between the test and reference pictures. There was, in fact, a remarkably high correlation between the subjective ratings for test objects 1 and 2. It may well be, however, that other combinations of test colours will give more meaningful objective assessments of the light sources. This seems to have been borne out by the fact that R_a (or D_a) correlates better with MSR than does $1000\overline{\Delta F_2}$.

The use of a *single set of lamps* is not regarded as a significant limitation of this work since the lamp set, in any event, comprised a diverse range of lamps with widely differing spectral properties.

The restriction of this work to only *one television system* was a practical limitation dictated by the circumstances under which the work was carried out. The spectral sensitivities of TV cameras do vary between different manufacturers, so there is no certainty that these results would have been precisely duplicated on another system. However, Opstelten and Beijer [18] and Taylor [8] have considered this problem, albeit in a slightly different context, and concluded that differences between individual practical camera systems are not particularly significant, always provided that the camera signals are matrixed, as was the case in the system used here.

The *group of observers* used in the subjective experiment consisted of 5 "expert" viewers and 18 "non-experts", i.e. 23 in all. This should be viewed against the CCIR recommendation [13] which may be summarized as follows:

Observers may be either expert or non-expert. The minimum number of non-experts should normally be 20, while the minimum number of expert observers should normally be 10.

This is interpreted as meaning that there should be at least 20 observers if fewer than 10 expert observers are used and only if all the the observers are experts, may their number be reduced to 10. In this context, a group of 23 observers may be considered to be sufficient to achieve valid subjective data.

The use of the *vertical split-screen* effect will undoubtedly have led to a greater discrimination between the reference and test sources than would have been the case had the pictures been presented sequentially. However, since the purpose of this work was to evaluate the impairment introduced by the use of gas discharge lamps, and to relate this to some objective measure of lamp performance, it was felt that the greatest possible sensitivity in the subjective test would be desirable. Suffice it to say that, as far as the acceptability of the impairment was concerned, the general consensus of the observers was that the great majority of the test lamps yielded "acceptable" colour reproductions. Only those lamps with colour rendering indices (R_a) of 45 or less gave results of marginal acceptability.

5.9 CONCLUSIONS

It has been shown that a need existed for a subjective scale to define the relative merits of various electric light sources as taking illuminants for colour television systems. The work described in this chapter has led to the derivation of a self-consistent subjective rating (the MSR) that represents the degree of impairment of a colour TV image resulting from changes in the TV scene illuminant. It is believed that this was the first such scale to have been established.

Attempts to correlate this subjective data with an objective (colorimetric) evaluation of the TV system's colour-reproduction performance met with only limited success. A different choice of test colours could possibly have led to better correlation in this experiment.

Further investigation established, however, that there was relatively good correlation between the MSR and the CIE colour rendering index (R_a) of each test source. This would seem to suggest that R_a gives a satisfactory measure of consistency in TV colour reproduction, and that it may therefore be unnecessary to formulate a separate consistency index for each light source.

It was also evident that – provided the illuminance levels are sufficiently high – the modern television camera is so adaptable as to be able to reproduce pictures of acceptable colour quality with the great majority of the lamps investigated.

There appears to be a good economic case to be made for the use in TV studios, and in outside broadcasts, of some of the gas discharge lamps with the higher R_a and MSR values. The metal-halide HID lamp has already become the standard source in exterior applications; and some recent publications [19, 20] indicate that it is now also beginning to make its appearance in TV studios.

The triphosphor fluorescent tube was also found to perform extremely favourably. It is not likely to find very ready acceptance in most applications, however, on account of its large dimensions and diffuse output. Two potential areas of application would seem to exist, though, in small studios (especially of the tele-conference type, where highlighting would probably be undesirable) and in small-to-medium sized indoor sports halls where high levels of diffuse lighting are also usually required.

There must also be a very strong economic case in favour of the High-Pressure-Sodium lamp, but at this stage it must be accepted that this lamp does lead to desaturation in a colour-balanced TV picture, so that it is unlikely to find acceptance among professional TV production staff. The possibility of improved versions of this lamp becoming available in the future must, however, be borne in mind.

5.10 FUTURE WORK

The most obvious area for further investigation would seem to be the assessment of as wide a range as possible of further varieties of source spectra for television lighting. The range available to the author has been limited in this investigation primarily by the lamp types being sold in South Africa by both importers and local manufacturers of HID lamps and fluorescent tubes – in other words, the commercially important lamp types – and there has been no access to developmental prototypes. This is where a lamp manufacturer with a development laboratory could be at an advantage.

There is, however, a relatively straightforward method of widening the range of source spectra available for practical experimentation, and that is by the blending of available spectra using combinations of two or more types of lamps, preferably housed within a single luminaire such that total (or at least *repeatable*) mixing of their radiant outputs is achieved. This approach has not yet been attempted, and would appear to be a fertile field for further investigation.

As far as the development of optimal spectra is concerned, another fruitful area of research would appear to be in the realm of mathematical modelling for, if accurate models of TV system response can be developed, it may be possible to predict what forms of lamp spectra need to be developed to optimise the design of TV lighting systems. Some work in this direction has already been undertaken within the working programme of CIE TC 1–11, but needs to be generalized and enlarged in scope to include newer camera types.

From the point of view of the television broadcaster, there is possibly also a need to look into sources of colour inconsistency other than the lighting systems – e.g. differing colour characteristics of different makes and types of television cameras; fading and discoloration of film stock; etc – and to attempt to find cost-effective solutions to these problems.

5.11 SUMMARY

Techniques were developed for the subjective and objective assessment of the performance of a colour television system, and were applied in evaluating the effects of changing the scene lighting.

A subjective scale (the MSR) has been established and it serves to rank the tested sources in terms of their acceptability for television lighting. It is believed that the MSR was the first such subjective scale to have been developed, and that a wider range of sources has been ranked by this scale than by any others. This scale appears to correlate with the CIE colour rendering index R_a.

There appear to be distinct economic advantages in the use of high efficacy gas-discharge sources for television lighting, and a basis has been provided for the economic comparison of television lighting systems employing different light sources.

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CHAPTER 6

EPILOGUE

6.1 REVIEW OF THE THESIS

It is perhaps worth emphasising at the outset that the essential purpose of this work was to obtain an accurate experimental assessment of the colour reproduction characteristics of a range of different types of electric light sources, in order to classify them in terms of their suitability as scene illuminants in colour reproduction applications, particularly in colour television. This dissertation has therefore, as a whole, been directed towards this aim; while additional and subsidiary subject matter has been introduced where necessary to expand on and elucidate the main theme.

Chapter 1 was a scene-setting chapter that served to introduce the major themes of the thesis; and it provided some historical perspective on the development of the author's work in the realm of colour science, in particular the areas of colour specification, colour measurement, colour rendering and colour reproduction.

Chapter 2 examined the principles of colour science in greater detail. It began by considering a series of definitions of COLOUR in order to introduce the underlying philosophy of colorimetry; and then went on to discuss the structure and functioning of the human visual system, since it was felt that a knowledge of the psychology and physiology of the human colour response is basic to all other aspects of colour science. The development of the science of colorimetry over the last 100 years or so was then surveyed, with specific emphasis on the systems of colorimetry that have been adopted and recommended by the CIE since 1931. It is impossible nowadays to undertake any meaningful work in quantitative colorimetry without recourse to the CIE systems of colour specification.

The purpose of Chapter 3 was to provide an overview of current electric-lamp technology, with specific emphasis on the major families of gas-discharge lamps. It included an analysis of the possible applications of these lamps in illumination for colour reproduction, and this led to the author's questioning of some of the preconceived notions in this sphere. It was accordingly concluded that a case could be made for performing a controlled experiment to determine the colour reproduction properties of these new light sources.

The experiment was planned in such a way that both physical (objective) and psychological (subjective) methods of assessment were to be used in evaluating the significance of the residual colour shifts in the colour reproductions obtained under the various test lamps. The physical approach was to employ colorimetric techniques to measure the magnitudes of these colour shifts, and it thus became necessary to consider ways and means of measuring the reproduced colours (and colour differences) using colorimetric instrumentation of acceptable performance.

Chapter 4 thus addressed the question of the design, construction and performance of different colorimeter systems. It included a survey of practical methods of colour measurement, and analysed their pros and cons, leading to a decision to construct a spectrophotometer system suitable for general-purpose colorimetry as well as for the specific needs of the project. This chapter also included details of a technique developed by the author whereby the performance of different colorimeter systems could be logically evaluated and compared on a statistical basis. It was shown that the performance of the author's design compared favourably with that of the spectrophotometer system operated at a national standardizing laboratory.

Finally, Chapter 5 provided the details of the actual experiment in which eleven different gas-discharge-type lamps were compared against the normal tungsten-halogen lamp for the purpose of lighting a television studio. The chapter described how both subjective and objective assessment techniques were developed to rank the test lamps in terms of their colour reproduction attributes. The mean subjective rating (MSR) of the test lamps appears to be a rather more valid measure of lamp performance than the Figure-of-Merit based on objective (spectrophotometric) data. According to this rating scale, several types of HID lamps and fluorescent tubes appear to be suitable for TV lighting.

6.2 COMMENTS AND CONCLUSIONS

From the point of view of the assessment of the colour-reproduction characteristics of electric lamps, it is believed that the work reported herein [1] constitutes the first unified set of experimental data to have been assembled for the specific purpose of defining the colour-reproduction attributes of a wide range of different lamps.

Subjective evaluation of the television colour reproduction obtained under each lamp type, was carried out making use of two test pictures – the one being a portrait of a girl and the other being a test colour chart – rating the one on an impairment (or Consistency) scale and the other on a preference (or Quality) scale. The two scales were, in fact, found to correlate very closely.

These experiments led to a Mean Subjective Rating (MSR) being attached to each type of lamp tested, as a measure of its colour-reproduction performance in terms of lighting for colour television. It was found that this MSR did not correlate particularly well with any physical measure of colour difference obtained on the same set of equipment, although there was a moderate degree of correlation with the CIE Colour Rendering Index of each test lamp.

Subjective assessments of the abovementioned form appear to be preferred by broadcasting authorities, presumably because they provide the most direct measure of the perceptibility of any changes (in this case, the different source spectra) introduced into the television system. It was certainly felt at the time that they provided a very revealing measure of the observers' reactions to the colour qualities of the various test sources.

There were two important differences between the recommendations of others (eg CIE SC–3.2) and the experimental techniques adopted in this work; first, the comparison scene was shown simultaneously with the test scene (not sequentially) and, secondly, an attempt was made to assess the degree of impairment. These techniques were originally dismissed by other authorities as being too sensitive. However, it is argued that one should, in fact, seek the most sensitive feasible measurement; and that this can then be scaled according to the needs of any particular application. Recent work within CIE TC1–11 appears to indicate that others may have come to agree with this approach [2].

In all these experiments, both physical and subjective, tungsten-halogen lighting was used as the standard reference illuminant. This source was chosen because of its spectral reproducibility and its almost universal application in television studios.

There are two particularly useful engineering conclusions to be drawn from this work. First, the light source attaining the highest score for subjective preference was the new-generation triphosphor fluorescent lamp. This indicates a possible area of application for this type of lamp as a studio light source in situations where lighting of a diffuse character may be demanded or preferred, particularly if the reputed aging processes in the lamp (that lead to colour changes through life) can be retarded. This lamp has significantly greater efficacy and longer life than the tungsten-halogen lamp.

The second conclusion of potential economic significance is that high-pressure-sodium sources, although ranked relatively low by comparison with some other sources, nevertheless yield colour reproductions of acceptable quality, and they ought, therefore, to find wider application in outdoor lighting installations, even where colour reproduction may be considered important. The golden colour cast of these lamps can be effectively removed from the television picture by balancing the system for a neutral grey scale. The effect on the reproduction is a reduction in the colour saturation of certain hues which, although perceptible, appears to be quite acceptable to a majority of viewers. High-pressure-sodium lamps have a very high efficacy coupled with an exceptionally long life; hence they are significantly more economical to run than many other competitive types of HID lamps.

The findings are thus of considerable economic importance for a television studio operator, since they demonstrate that colour reproductions of an acceptably high standard can be achieved when making use of certain kinds of light sources that have previously been regarded as unusable or unsatisfactory for colour reproduction applications.

As regards measuring equipment and instrumentation, this dissertation has included a description of a newly-designed spectrophotometric colorimeter [3] that was used in the physical measurement of colour differences in the form required for the computation of Figures-of-Merit for the test lamps used in the colour reproduction experiments.

This system has been constructed around two identical monochromators that can be operated singly, or paired as a double-monochromator, with a choice of two alternative photomultiplier detectors. The philosophy here was to provide a flexible system with several possible configurations, to permit useful measurements to be made of the spectral reflectance, transmittance and fluorescence of different materials and surfaces, as well as the spectral radiance of sources, over the wavelength range from 300 to 800 nm. This represents a greater spectral bandwidth and a wider range of applications than considered strictly necessary for the project, but other uses of the system had to be borne in mind in designing it as economically as possible in the long-term sense.

The performance of the spectrophotometer system was measured by making use of a novel technique that had been developed previously [4] to enable quantitative comparisons to be made between a number of different colorimetric instruments that were used in the earlier stages of this work. From this assessment, it was concluded that a high degree of confidence could be placed in the colour measurements obtained on this system.

6.3 CLAIMS OF THIS THESIS

It is the author's belief that the majority of the aims of the project have been met.

First, and most important, it would seem that a satisfactory set of subjective evaluations has been obtained, and that this information can be used to indicate the performance of a colour television system in conjunction with a variety of different scene illuminants.

Predictably (in light of remarks by other authors, eg Reference [5]) there was not very good correlation between the subjective assessment and the physical Figure-of-Merit for the sources that were tested by both methods. It is, however, argued that the subjective data gives the more meaningful measure of performance for normal operation of the television system.

It is claimed that the subjective evaluations reported in this thesis (and originally published in 1981 [1]) constitute an original contribution to the literature on this topic. It is true that other contributors have more recently carried out similar work using more professional equipment [6,7], but this was published some years after this author's work. In spite of the greater refinement in the techniques available to these other workers, their findings do not appear to differ to any significant degree from those reported here, although opinions differ as to whether a television consistency index will characterize lamps more effectively than the colour rending index, R_a. As new lamp types evolve and are developed in the market place, there will of course be a continuing need to characterize their properties by the use of techniques similar to these.

The second substantive claim of this thesis is that the author has succeeded in the design, construction, testing and application of a low cost spectrophotometer system [3] with novel features, particularly with regard to its flexibility and adaptability. Although employing commercial "building blocks", the author has attempted to employ an independent approach to the design of a system that would be suitable, not only for the immediate needs of the present project, but also for a much wider range of possible applications in the author's teaching and research environment.

It is also claimed that the author has developed a technique for the classification of the colorimetric performance [4] of this spectrophotometer system (or any other colorimeter) and has applied this technique satisfactorily in this work.

Finally, as the outcome of the subjective testing procedure already mentioned, there are strong indications that many of the HID light sources that have conventionally been regarded as unsuitable for television lighting applications, may be able to yield more-acceptable system-performance than has heretofore been believed. Because of the high efficiencies of these sources, this finding has obvious economic significance in a world of rapidly spiralling energy costs [8].

It is therefore believed that this work will be of value to the designers and users of colour reproduction equipment, and the designers and users of lighting installations where such equipment may be employed, as well as to electric lamp manufacturers who are attempting to produce optimized lamp spectra for colour reproduction purposes.

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APPENDIX A :

Copy of Paper :

A.N. Chalmers and C.J. Kok: Accuracy and Repeatability in Colorimetry, Color 81 Berlin, Proc. 4th Congress AIC *Paper Po 8 (1981).*

P08

Andrew Neil Chalmers, Department of Electronic Engineering, University of Natal, Durban, and Christoffel Johannes Kok, National Physical Research Laboratory, C.S.I.R., Pretoria (South Africa):

Accuracy and Repeatability in Colorimetry

This paper reconsiders some earlier findings in this area and goes on to discuss some findings from an extensive series of measurements of a set of material colour samples carried out on several colorimeters differing in their principles and methods of operation. These instruments differ markedly in their accuracy and repeatability, and it is demonstrated that repeatability is influenced also by sample chroma and lightness.

Après une considération des résultats précédants on présente des mesures nouvelles que l'on a gagnées par séries extensives avec des couleurs d'objet et avec des colorimètres de construction différente. Ces instruments dévient considérablement en exactitude et en précision de répétition l'un de l'autre, et on a trouvé que la précision de répétition dépend aussi de la saturation et de la clarté des échantillons.

Nach einem Überblick über einige bisherige Ergebnisse werden neue mitgeteilt, die aus einer Reihe von Messungen an Körperfarben mit Farbmeßgeräten verschiedener Konstruktion gewonnen worden sind. Diese Instrumente weichen beachtlich in Meß- und Wiederholgenauigkeit untereinander ab, und es hat sich gezeigt, daß die Wiederholgenauigkeit auch von der Sättigung und Helligkeit der Proben abhängt.

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Introduction:

In an earlier assessment of a photoelectric colorimeter that was being used in a colour reproduction study (Chalmers 1979) it was found that there was a clear relationship between the lightness of each sample and the repeatability of its measured chromaticity. The way that this relationship was expressed was in terms of the net standard deviation of the measured chromaticity s(u,v,w) as a function of the normalized sample lightness Y,

where $s(u,v,w) = \{s^2(u) + s^2(v) + s^2(w)\}^{\frac{1}{2}}$
and s(u) = standard deviation of measured u-coordinate
s(v) = standard deviation of measured v-coordinate
s(w) = standard deviation of measured w-coordinate

as determined in the CIE 1960 (u,v,w) system. It was found that the form of the relationship in this instance was a reciprocal function :

$$Y.\ s(u,v,w) = \text{constant}.$$

This form of relationship seems quite plausible on the grounds that a lighter sample will reflect more light into the colorimeter and the measured result would therefore be less influenced by noise, dark current, stray light and other extraneous factors leading to deviations in the calculated results. There would thus appear to be some grounds for assuming that this form of relationship may be more generally applicable.

It was decided, therefore, to examine another body of data that had been accumulated in the calibration of a set of Munsell colour swatches for use as in-house colorimetric standards. A feature of this study is that it also permits some comparisons to be made of the performance of the three different types of colorimeter that have so far been used in the measurement of these samples, viz. a visual colorimeter, a spectrophotometer and a mask colorimeter, details of which have been given in a previous paper (Chalmers and Kok 1977). The calibration samples were 20 swatches that had been selected from a Munsell Color File to give a reasonably representative range of Hues, Values and Chromas, including two neutral greys.

Results:

Each sample was measured on nine separate occasions: four times on the visual colorimeter, twice on the spectrophotometer and three times on the mask colorimeter. Each colour determination comprised a single, complete set of readings of all twenty samples on one instrument, and was quite separate from any other determination on that instrument. In the case of the visual colorimeter, the results quoted here embody the work of two observers each of whom carried out two separate colour determinations of the twenty samples. In all cases, the measurements were performed using the 45°/0° geometry, under both illuminant A and illuminant C, but this paper is confined to an analysis solely of the illuminant C data.

Using CIELAB coordinates, the mean measurement of each sample on each instrument has been compared with the overall mean of the nine measurements of each sample, and also with the Munsell Renotation data (Wyszecki and Stiles 1967) transformed to (L* a* b*) form. The standard deviation s(L* a* b*) of the measurements obtained for each sample on each instrument has also been determined,

where $s(L^* a^* b^*) = [s^2(L^*) + s^2(a^*) + s^2(b^*)]^{\frac{1}{2}}$
and $s(L^*)$ = standard deviation of measured L*-coordinate
$s(a^*)$ = standard deviation of measured a*-coordinate
$s(b^*)$ = standard deviation of measured b*-coordinate.

here is no evidence of the previously described reciprocal relationship etween standard deviation and Y. On the contrary, both the pectrophotometer and the mask colorimeter show some evidence of (L* a* b*) and s(u,v,w) increasing with Y (and with L*) while the easurements on the visual colorimeter yield standard deviations that ppear to be independent of sample lightness.

he r.m.s. standard deviation s of the three instruments together has lso been computed, and the dependence of s on sample chroma C is llustrated in Fig. 1. In Fig. 2 E_{rms}, the r.m.s. deviation of the hree instruments' readings from the Munsell Renotation for each sample, as been plotted against C. Linear regression analysis indicates that n both cases the deviations apparently increase with chroma. Each of he instruments taken independently yields similar results. Since the eflectance spectrum of the high-chroma samples tends to be steeper and arrower than for other colours, this finding would seem to be ndicative of the presence of wavelength errors. A new analysis of the arlier data obtained on the photoelectric colorimeter shows no evidence f this type of behaviour.

t is apparent that no general conclusions can be drawn concerning the onfidence with which samples of differeing lightnesses and chromas can measured on different instruments. It seems likely that different rror mechanisms will predominate in different instruments and that they y be influenced by the measurement technique. Other factors that nnot be excluded but which require further investigation, e: (a) possible non-linearities in the instruments: and (b) the ssibility that the two different sets of samples used in the earlier d in the current experiments could have introduced some form of bias to the results.

knowledgements:

work described in this paper has been financed by a Research Grant om the South African Council for Scientific and Industrial Research se support is gratefully acknowledged. ANC wishes to thank the rector of the National Physical Research Laboratory of the CSIR for rmission to make use of the laboratory facilities of that institute, the Staff of the Precise Physical Measurements Division for their operation and assistance.

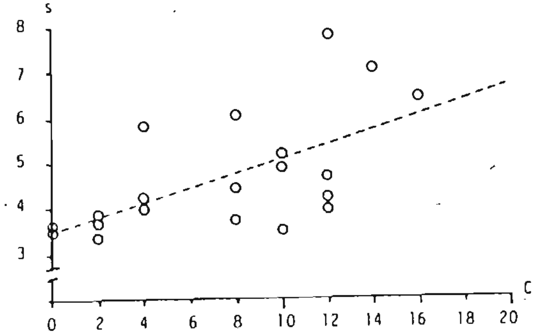

FIG 1: Standard deviation of measured colour in the CIELAB system : (9 measurements of 20 samples on 3 instruments)

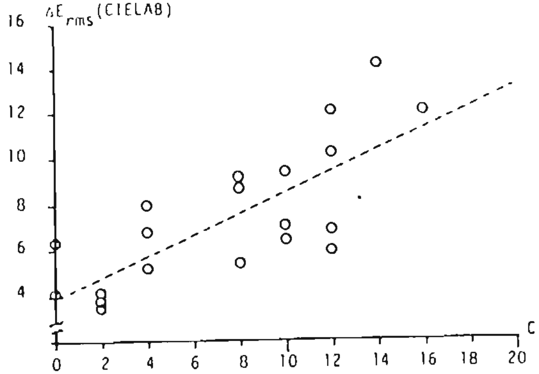

FIG 2: RMS deviation of measured colour from Munsell Renotation (Mean measurement of 20 samples on each of 3 instruments)

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APPENDIX B :

Copy of Paper :

A.N. Chalmers and G.R. Holmes: TV Picture Fidelity, Paper presented at 28th Congress SANCI Capetown *(1981).*

SOUTH AFRICAN NATIONAL COMMITTEE ON ILLUMINATION

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T V PICTURE FIDELITY

The subjective assessment of colour television picture fidelity using a variety of scene illuminants

by

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1. INTRODUCTION

New types of high efficacy discharge lamps are being used increasingly to light areas such as sports stadia, arenas, exhibition halls, gymnasiums and, generally, lighting areas where colour T.V. outside-broadcasts may be made. Their high efficacy, good optical control and long life result in lighting systems that produce more light, less heat and a lower overall cost per lumen-hour than incandescent lamp systems.

Questions remain however, as to the effect these light sources have on colour T.V. picture quality. This paper thus describes an investigation conducted into the subjective responses of viewers to television reproductions of test objects illuminated by various gas discharge lamps, and an analysis of the results obtained.

Since tungsten halogen lamps are used almost universally for T.V. studio lighting, test source reproductions were viewed alongside reproductions of the identical test object illuminated by tungsten halogen lighting. This facilitated a subjective comparison, made with the aid of grading scales, as to the relative quality of the test source reproduction, using the tungsten halogen reproduction as reference.

2. OUTLINE OF THE TEST PROCEDURE AND SYSTEM

2.1 Test lamps investigated

After an initial survey of available discharge lamps, several different types were chosen which were thought may lend themselves to applications (in the sports world particularly) that might attract T.V. coverage. A number of fluorescent tubes were also included on the grounds that they represent possible alternatives for indoor situations.

Appendix 1 contains details of the test sources investigated.

2.2 Production of video comparison tapes

Ideally one camera should be used to shoot both the test-source and reference-source reproductions. However, the only way in which a side-by-side comparison of the reproductions could be obtained (utilizing a single monitor) was to use a vertical split screen effect and two cameras. The reference source reproduction always appeared on the right-hand side of the screen.

2.2.1 VIDEO TAPE PRODUCTION

The subjective assessment tape consisted of a series of comparisons of two test objects viewed under the test sources listed in Appendix 1.

(i) Test Object 1 - A commercially-produced Colour Rendition Chart[1]. This Chart has been developed to facilitate quantitative or visual evaluation of colour reproduction processes employed in photography, T.V. and printing. The 4 x 6 array of patches, each 50 mm square, includes spectral simulations of light and dark human skin, foliage, blue sky and a blue flower (chicory). Additive and subtractive primaries and a six-step neutral scale are included for analytical studies, and other colours fill a wide gamut. The names of the colours, their colorimetric designations in the CIE 1931 system and the Munsell system, and the ISCC-NBS names, are given in Appendix 2.

(ii) Test Object 2 - An ink-printed reproduction of a photographic portrait of a girl. The validity of such a test object is possibly questionable in that the printing inks used were only metameric and not spectrally representative of light skin tone. The reproductions were pleasing, however, in that they were more easily assessed than the skin tone patches of test object 1, and were visually acceptable as representative of skin tone.

2.2.2 PRESENTATION OF TEST SOURCES AND OBJECTS

The sequence in which the test sources were presented was random since their position on the tape was determined by lottery. Three of these sources were reintroduced randomly to assess a particular viewer's consistency, as well as a tungsten-halogen versus tungsten-halogen comparison to judge viewers' evaluation capability.

Colour chart comparisons were made for roughly 30 seconds while those for test object 2 were made for approximately 20 seconds. Provision was, however, made for the viewer to become accustomed to making subjective assessments of this nature, by making the comparisons run for longer at the beginning of the tape, slowly decreasing to 30 and 20 seconds for test objects 1 and 2 respectively.

2.3 System elements affecting picture reproduction fidelity

While using the T.V. facilities at the Audio-Visual Centre of the University of Natal, various elements within the system were noted to influence picture reproduction fidelity. These are dealt with briefly below.

1) Illumination. The spectral content of the light source used, together with the spectral reflectance of the object being televised, caused variations in the hue, saturation and lightness of the reproduced test object colours.

2) T.V. Cameras. Studio cameras 1 and 2 were used and it soon became evident that their responses were different. When balanced to a grey scale, under the normal studio lighting, the reproduction of camera 1 was unnaturally red. It was not possible to compensate completely for this effect.

Because of this difficulty, the assessment tape was made in two sections, each resembling a short television programme. Part I, about 20 minutes long, contained 15 scenes illuminated by all the test sources (one per scene) and included a few repeats as consistency checks. In all these scenes, camera 1 was used with the reference illuminant to produce the picture on the right half-screen. Part II, about 10 minutes in length, comprised 7 scenes in each of which camera 2 was used with the reference illuminant for the right half-screen picture. The test illuminants used for Part II of the tape were randomly selected from the group used for Part I.

The two cameras, although of the same make and model, had different lens systems. Misalignment between the scanning circuits of the two cameras was noticeable when comparing the reproductions of Test object 2 side by side. With camera 1 the girl's features were noticeably sharper than with camera 2.

3) Size inconstancy. Difficulty was also experienced in trying to maintain a constant size of the girl's face. The reason was twofold:
i) Between shots of test object 2 the test source camera was being zoomed onto half of the Colour Rendition Chart to produce a second Video Tape intended to be used for detailed quantitative comparisons.
ii) The aspect ratio of test objects 2 placed side by side was not 4:3 as was the case for test objects 1 - the zoom of both cameras thus had to be used when shooting test object 2 to obtain better screen utilization.

These constant adjustments made it difficult to maintain a constant size for test object 2 in all shots and the best that could be achieved was to adjust the facial sizes in each comparison pair of pictures to be approximately equal.

A noticeable effect of this was that the reference reproduction of test object 2 appeared to change hue and saturation slightly, and appeared more acceptable in some scenes than in others.

4) Cassette Recorders/Playback systems. Two Videocassette Recorders and Playback systems of the same make were used in making the relevant video tapes. Any one tape was, however, completed on a single recorder. There was a bandwidth limitation in that the recorders have a 2,5MHz bandwidth compared with the 3,3MHz bandwidth of the cameras. This effect is constant and was accepted as unavoidable.

5) Viewing Conditions. The assessment of picture reproduction fidelity varies with ambient viewing conditions. For this reason, a carefully controlled viewing environment was set up for this experiment.

6) Videocassettes. Three different makes of video tapes were used: The assessment tape was completed on a single tape while one of each make was used in the production of the "measurement" tape. Possible discrepancies due to tape characteristics could thus occur in trying to correlate measured and subjective results. This has not yet been investigated.

7) Monitors. During recording, the scene was displayed on two different makes of studio monitors, as well as on a domestic type receiver. Noticeable differences between the monitors were evident at all times.

Since the viewing environment for the subjective assessment experiment had to be set up outside the studio, the domestic-type equipment was used for this part of the experiment.

3. SUBJECTIVE EVALUATION AND THE USE OF GRADING SCALES

The ultimate purpose of tests of this type is to determine the acceptability of some impairment in the system. In this case it is to evaluate the impairment introduced by the use of gas discharge lamps and to find whether this significantly reduces the acceptability of colour T.V. picture quality. The details of the method of assessment, as set out hereunder, have been based as far as possible on the recommendations of the CCIR (International Radio Consultative Committee).[2,3]

1) Observers. Observers may be either expert or non-expert. The minimum number of non-experts should normally be 20, while the minimum number of expert observers should normally be 10.

2) Grading Scales. According to the nature of the problem it may be more appropriate to use a quality scale, impairment scale or comparison scale. After careful consideration of the problem and the grading scales in general use, it was decided to use a quality scale for the assessment of test object 1 and a simple comparison scale for test object 2. These are listed below:

5 POINT GRADING SCALES USED :

QUALITY SCALE		COMPARISON SCALE	
1	EQUAL	+2	MUCH BETTER
2	SLIGHTLY DIFFERENT	+1	BETTER
3	DIFFERENT	0	EQUAL
4	VERY DIFFERENT	-1	WORSE
5	EXTREMELY DIFFERENT	-2	MUCH WORSE

---

3) Test Pictures. About 5 test pictures should normally be used. These should be more critical than an average picture and, where appropriate, should include pictures derived from a colour camera viewing scenes containing bright saturated colours.

In this assessment, due to the large number of lamp types investigated, only two test objects were used; however both contained some bright saturated colours.

4) Viewing Conditions. The CCIR recommends a set of well-defined standard viewing conditions, the purpose of which is to ensure that the observers performing subjective evaluations are correctly adapted (in respect of both the luminance and the colour of the surroundings) before and during their observations.

The actual viewing conditions achieved in the experimental set-up were a very close approximation to the CCIR recommendations.

5) Presentation. The pictures and impairments should be presented in a random sequence with the proviso that the same picture should never be presented on two successive occasions with the same or different levels of impairment.

This was adhered to by first showing test object 1 and then test object 2 under each light source used. When a light source was reintroduced for consistency assessment, the two identical light source reproductions never appeared consecutively.

A further point worth noting is that to obtain a true overall assessment, the effect of sequence of presentation should be investigated. However, since such a large range of light sources was investigated, viewers could not be expected to view the assessment tape as presented, as well as permutations thereof.

Lecture theatre G-01 in the Electrical Engineering building at the University of Natal proved to be a very convenient venue in which to set up standard viewing conditions, and all the subjective evaluation experiments were carried out in this room.

6) Summary. The CCIR recommendations thus suggest guidelines to assist in formulating a considered experimental assessment programme. This is in an attempt to standardise the methods of analysing and presenting experimental data relating to the assessment of picture impairment, which until recently have varied considerably among experimenters. These guidelines have been followed as closely as possible within the framework of the experiment.

4. RESULTS

A total of 23 observers has so far made subjective evaluations of the test reproductions. Five of the viewers were regarded as "expert" (18 were novice) and four were female (19 were male).

Since each of the gradings in the assessment scales was assigned a numerical value, it was possible to compute a mean subjective score (for the "average" reaction of all observers) for each test source. Statistically, the mean is the most efficient estimation of the central tendency of the data, but gives no information about the distribution of opinions regarding a given impairment condition. For each reproduction a maximum and minimum rating is thus given.

Other statistical methods of analysis do exist but it was felt that in this particular application an average rating best describes the acceptability of a reproduction.

Comparing the average scores for Part I and Part II of the tape it was found that, for both test objects 1 and 2, the evaluation rating of the respective test sources are consistently worse in Part II. Obviously the visual difference noted in similar reproductions of the same test source, using different cameras, has been verified by subjective assessment. (See Section 2.3 (2)). These differences are tabulated overleaf:

PART I TEST SOURCE		14	6	4	11	10	3&12	7
PART II TEST SOURCE		16	17	18	19	20	21	22
MODULUS OF DIFFERENCE IN RATINGS	TEST OBJECT 1	0,39	0,44	0,52	0,57	0,40	0,61	0,44
	TEST OBJECT 2	1,83	0,00	0,69	1,13	1,87	0,13	1,04

AVERAGE DIFFERENCE TEST OBJECT 1	0,48	CORRECTION FACTORS
AVERAGE DIFFERENCE TEST OBJECT 2	0,95	

Using these correction factors it is possible to obtain the "true subjective ratings" by taking camera 2 (say) as reference (since its reproductions appeared visually more acceptable.)

Knowing that camera 1 produces a poorer reproduction, this means that in Part I the reference used for comparison (viz the tungsten-halogen reproduction) was not as good as it should have been, and hence the test sources would have obtained higher ratings than they should have.

Hence, in Part I the "true subjective rating" is obtained by subtracting the correction factors from the "average rating of the 23 viewers". The "true ratings" are given below:

TEST SOURCE	TRUE AVERAGE RATING OF 23 VIEWERS	
	TEST OBJECT 1	TEST OBJECT 2
1	1,69	-1,30
2	2,39	-1,47
3	2,65	-2,04
4	2,26	-1,43
5	1,74	-0,95
6	1,91	-2,17
7	2,04	-0,78
8	1,61	-0,47
9	1,65	-0,56
10	1,95	-0,08
11	1,30	-0,34
12	1,95	-2,52
13	2,48	-1,82
14	1,78	+0,18
15	3,00	-2,47

Part II of the assessment tape was thus included for the sole purpose of finding the correction factors and hence the above "true average ratings" due to the cameras' different responses.

5. CONCLUSIONS

Comparing the "average rating of 23 viewers", "average rating of the 19 male viewers", "average rating of the 4 female viewers" and "average rating of the 5 expert viewers", the numerical averages for the respective test object and test source are very similar, as also is the general trend of the source ratings. However not much reliance can be placed in this correlation since there were only 4 female observers and only 5 expert viewers. A valid comparison can thus not be made at this stage and more female and expert observers are needed. A comparison between the different age groups was also not possible nor was a comparison between different race groups, with the limited numbers of observers. Another investigation that could possibly be carried out in the future is a comparison between "normal" and "colour blind" observers.

An interesting fact was that the Colour Rendition Chart appeared to fail as a test object for subjective evaluations of colour T.V. picture reproductions since, only with lamps known to have poor colour rendering properties, did the test chart reproductions become noticeably poor enough to make a valid evaluation. In most test scenes it seemed to differ only slightly with differences in the illuminants and it was difficult to determine whether the difference between the two charts viewed in any one scene was due to the difference in camera responses or due to the differences in the sources.

Test object 2, however, showed much more noticeable quality changes, and evaluation was far easier. This was possibly because skin tones are so well embedded in our minds that evaluation is made easier.

Regarding the acceptability of the various lamp types as T.V. scene illuminants, the following tabulation, based on the scores achieved with Test Object 2, gives an approximate rank order of the sources:

AVERAGE RATING R WITH TEST OBJECT 2	TEST SOURCE NUMBER	TEST SOURCE DESCRIPTION
$+1 \geq R \gneqq 0$	14	Triphosphor fluorescent tubes (white)
$0 \gneqq R \gneqq -1$	10	Coated Metal halide lamp
	11	Tungsten-halogen comparison lamp
	8	High Efficacy fluorescent tubes (warm white)
	9	Clear metal halide lamp
	7	Mercury/filament blended lamp
	5	Same as no 8
$-1 \gneqq R \gneqq -2$	1	Medium Efficacy Fluorescent tubes (white)
	4	Phosphor-coated Mercury lamp (modern type)
	2	Deluxe Mercury lamp
	13	Same as No. 2
$-2 \gneqq R \gneqq -3$	3	High pressure sodium lamp
	6	High Efficacy Fluorescent tubes (white)
	15	Phosphor coated Mercury lamp (early type)
	12	Same as no. 3

There is insufficient evidence at this stage to enable great significance to be attached to this table, since the numbers of observers were small and the sampling of the test sources and test objects would have to be expanded considerably in scope. Also the fact that test source no. 11 achieved a negative score (instead of zero), plus the discrepancies in scores between nos. 5 & 8, 2 & 13, and 3 & 12, suggests that there are small inconsistencies in the assessment technique.

However, it was evident that all sources achieving scores higher than -1 produced very satisfactory colour T.V. reproductions. These included Metal-halide and Mercury-blended lamps as well as two different varieties of Fluorescent tubes.

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APPENDIX 1
Test Sources Investigated

LAMP CATEGORY	TEST SOURCE NO.	LAMP DESCRIPTION
(A) Fluorescent Tubes 1200 mm 40 W	5 & 8	1. High-Efficacy Warm White
	1	2. Medium-Efficacy White
	6	3. High-Efficacy White
	14	4. Trisphosphor White
(B) High Intensity	3 & 12	1. Coated High-Pressure-Sodium
	15	2. Phosphor-coated Mercury (early type)
Discharge	4	3. Phosphor-coated Mercury (Modern type)
Lamps	2 & 13	4. Deluxe Phosphor-coated Mercury
400 W	7	5. Mercury/Filament blended (500W.)
(unless otherwise stated)	10	6. Coated Metal-Halide (375W.)
	9	7. Tubular Metal-Halide
(C) Reference/Studio Lamps	11	1. Tungsten-halogen filament lamps

APPENDIX 2
Colour Rendition Chart : Colour Patch Names and Specifications

		CIE (1931)[a]			Munsell Notation		
No.	Name	x	y	Y	Hue	Value/Chroma	ISCC/NBS Name
1.	dark skin	.4002	.3504	10.05	3.05YR	3.69/3.20	Moderate brown
2.	light skin	.3773	.3446	35.82	2.2YR	6.47/4.10	Light reddish brown
3.	blue sky	.2470	.2514	19.33	4.3PB	4.95/5.55	Moderate blue
4.	foliage	.3372	.4220	13.29	6.65GY	4.19/4.15	Moderate olive green
5.	blue flower	.2651	.2400	24.27	9.65PB	5.47/6.70	Light violet
6.	bluish green	.2608	.3430	43.06	2.5BG	7/6	Light bluish green
7.	orange	.5060	.4070	30.05	5YR	6/11	Strong orange
8.	purplish blue	.2110	.1750	12.00	7.5PB	4/10.7	Strong purplish blue
9.	moderate red	.4533	.3058	19.77	2.5R	5/10	Moderate red
10.	purple	.2845	.2020	6.56	5P	3/7	Deep purple
11.	yellow green	.3800	.4887	44.29	5GY	7.08/9.1	Strong yellow green
12.	orange yellow	.4729	.4375	43.06	10YR	7/10.5	Strong orange yellow
13.	Blue	.1866	.1285	6.11	7.5PB	2.90/12.75	Vivid purplish blue
14.	Green	.3046	.4782	23.39	0.1G	5.38/9.65	Strong yellowish green
15.	Red	.5385	.3129	12.00	5R	4/12	Strong red
16.	Yellow	.4480	.4703	59.10	5Y	8/11.1	Vivid Yellow
17.	Magenta	.3635	.2325	19.77	2.5RP	5/12	Strong reddish purple
18.	Cyan	.1958	.2519	19.77	5B	5/8	Strong greenish blue
19.	white	.3101	.3163	90.01	N	9.5/	White
20.	neutral 8	.3101	.3163	59.10	N	8/	Light gray
21.	neutral 6.5	.3101	.3163	36.20	N	6.5/	Light-medium gray
22.	neutral 5	.3101	.3163	19.77	N	5/	Medium gray
23.	neutral 3.5	.3101	.3163	9.00	N	3.5/	Dark gray
24.	black	.3101	.3163	3.13	N	2/	Black

[a] The values listed under Y are % luminous reflectance factors. The chromaticity coordinates are based on CIE Illuminant C.

GLOSSARY

Adaptation: The autonomous ability of the visual system to adjust its response in accordance with the luminance and the spectral power distribution of the visual stimulus, modified by the immediate past stimulus.

Anomalous Trichromat: A trichromat whose visual colour matching is significantly different from that of the majority of observers.

$BaSo_4$: Barium Sulphate (chemical formula).

CAMAC: Computer Aided Measurement And Control.

Candela: The unit of luminous intensity.

CCIR: International Radio Consultative Committee (responsible for international standards in radio and TV).

Chromatic Adaptation: Adaptation to the colour appearance of, and colour effects produced by, light sources differing in spectral power distribution.

Chromaticity: A two-dimensional representation of the chromatic nature of a colour stimulus (i.e. excluding lightness or brightness as the third parameter in a colour definition).

Chromaticity Diagram: A plane diagram that can be used to represent the colour attributes (excluding lightness or brightness) of any colour stimulus or of any mixture of stimuli. The chromaticity of a given colour stimulus is represented by a single point on the chromaticity diagram, and mixtures of stimuli by straight lines joining the relevant points on the diagram.

Chromaticness: A (subjective) measure of the degree of purity or saturation (or "vividness") of a colour stimulus. The neutral series (white, greys and black) have zero chromaticness.

CIE: International Commission on Illumination (Commission Internationale de l'Eclairage).

CIELAB: The CIE–1976 ($L^*a^*b^*$) colour system.

CIELUV: The CIE–1976 ($L^*u^*v^*$) colour system.

CIE–1931 Chromaticity Diagram: Chromaticity diagram in which the CIE–1931 chromaticity coordinates, x and y, are used to represent the appearance of colour stimuli.

CIE–1960 Chromaticity Diagram: Approximate UCS diagram, adopted provisionally by the CIE, and employing the CIE–1960 chromaticity coordinates, u and v. A projective transformation of the CIE–1931 (x,y) diagram.

CIE–1976 Chromaticity Diagram: Approximate UCS diagram, currently recommended by the CIE, and employing the CIE–1976 chromaticity coordinates, u' and v'. A projective transformation of the CIE–1931 (x,y) diagram.

CIE–1976 ($L^*a^*b^*$) Colour Space: Known as CIELAB space: A three-dimensional colour space, based on cube-root transformations of the tristimulus values of the colour stimulus, having no associated chromaticity diagram.

CIE–1976 ($L^*u^*v^*$) Colour Space: Known as CIELUV space: A three-dimensional colour space, based on a combination of linear and cube-root transformations of the tristimulus values of the colour stimulus, and associated with the CIE–1976 (u',v') chromaticity diagram. Replaces the CIE–1964 ($U^*V^*W^*$) uniform colour space.

Colorimetry: The systematic approach to the measurement and specification of colour in light sources and in reflecting and transmitting surfaces of all kinds.

Colour Blindness: Colloquial term applied loosely to monochromatism, dichromatism and anomalous trichromatism.

Colour Consistency Index: Applied to a light source: A measure of the degree to which the reproduced colours of objects (on a television screen, for example) taken under that light source, conform to those of the same objects taken under a reference illuminant, suitable allowance being made for maintaining neutral balance in both cases.

Colour Fidelity: Applied to a colour reproduction system: A measure of the degree to which the reproduced colours of objects conform to those of the original objects, under specified conditions.

Colour Matching Functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$: Three spectral weighting functions that, as a set, represent the average response of normal trichromatic observers to each wavelength within the visible spectrum.

Colour Quality: As applied to a colour reproduction system: An assessment (usually subjective) of the degree to which the reproduced colours of objects appear to conform to some standard.

Colour Reproduction System: A generic term for processes such as photography, printing and television which attempt to recreate images of scenes in such a way that the colours in the images are recognizable replicas of the colours of the original objects.

Colour Rendering Index: Applied to a light source: A measure of the degree to which the colours of objects conform to those of the same objects under a reference source, with suitable allowance for changes in the state of chromatic adaptation.

Colour Space: A geometric representation of colours, usually in three-dimensional space.

Colour Stimulus: Radiation of a given power and spectral composition, entering the eye and producing a sensation of colour.

Colour Temperature: The absolute temperature of a full radiator that would emit radiation of the same chromaticity as the source under consideration.

Cones: The light-sensitive nerve-endings in the human retina that are responsible for photopic vision. They exist predominantly within the fovea, and appear to be of three types, described, approximately, as red–, green–, and blue-sensitive.

Correlated Colour Temperature: The absolute temperature of the full radiator, the chromaticity of which is nearest to the point representing the chromaticity of the source under consideration, in the CIE–1960 (u,v) uniform-chromaticity-scale diagram.

CSIR: (South African) Council for Scientific and Industrial Research.

Dichromat: A colour-deficient observer whose colour response is two-dimensional.

DMM: Digital Multimeter.

DVM: Digital Voltmeter.

Figure-of-Merit: As used in this thesis: A numerical measure of the performance of a colour reproduction system, derived from measured differences in colour or chromaticity between the object colours in a test reproduction and in either a reference reproduction (colour consistency) or a reference scene (colour fidelity).

Fovea: The central portion of the retina in the human eye, where the image is formed of an object on which the observer fixates.

Full Radiator: Also called "black body radiator" or "Planckian radiator": A thermal radiator obeying Planck's radiation law, and having the maximum possible radiant output at all wavelengths for a given temperature.

GPIB: General Purpose Interface Bus (also Known as HPIB and IEEE–488).

HID: High Intensity Discharge (lamp).

HPS: High Pressure Sodium (lamp).

HT: High Tension (or, High voltage).

IEEE–488: Standard drawn up by the Institute of Electrical and Electronic Engineers (USA) for the General Purpose Interface Bus.

Illuminance: The luminous flux per unit area, incident on a surface element. Unit: lux (or, lumen per square metre).

Illuminant: In general: A source of light.

Illuminant A: A standard illuminant defined by the CIE as a full radiator operated at a temperature of 2856K.

Illuminant C: A standard illuminant defined by the CIE as representing "average daylight" (effectively within the *visible* range of wavelengths only) with a correlated colour temperature of approximately 6774 K.

Illuminant D_{65}: A standard illuminant defined by the CIE as representing a phase of daylight with a correlated colour temperature of approximately 6504 K.

Intensity: Luminous intensity.

IR: Infrared (radiation, etc).

Irradiance: The radiant flux per unit area, incident on a surface element. (Unit: watt per square metre.)

ISCC: Inter-Society Color Council (USA).

ISCC-NBS Designations: A colour-naming system for surface colours, devised jointly by the Inter-Society Color Council and the National Bureau of Standards (USA), based on a simplified representation of the Munsell Color System.

Isomeric Match: A match between two colour stimuli possessing identical spectral power distributions.

JND: Just Noticeable Difference (of colour or chromaticity).

LPS: Low Pressure Sodium (lamp).

Lumen: The unit of luminous flux: the luminous flux associated with a radiant flux of $1/683.V_\lambda$ watt at any wavelength λ (in air).

Lumen Maintenance: Of a lamp: The gradual deterioration of lumen output with operating time; the percentage of initial lumens produced by the lamp after a stated time.

Luminance: Of an area source: The apparent luminous intensity per unit projected area of an infinitesimal surface element on a luminous surface. Unit: candela per square metre (or, nit).

Luminous Flux: A quantity associated with radiant flux, as determined by the sensitivity of the normal human eye to the various component wavelengths constituting the radiant flux.

Luminous Intensity: Of a point source: The concentration of luminous flux per unit solid angle in an infinitesimal element of solid angle having its apex at the source. Unit: candela (or, lumen per steradian).

Lux: The unit of illuminance.

MacAdam Ellipses: A set of 25 ellipses plotted in different regions of the CIE–1931 (x,y) diagram. Each ellipse represents the same subjective judgement of chromaticity difference.

Metameric Match: A match between two colour stimuli possessing *non-identical* spectral power distributions.

Monochromat: A colour-deficient observer whose colour response is one-dimensional.

Monochromatic Stimulus: A colour stimulus comprising a very small range of wavelengths, such that it can effectively be described by a single wavelength.

MSR: Mean Subjective Rating (see Chapter 5).

Munsell Color System: A system of surface colour specification originated by A. H. Munsell in the USA, and exemplified in various collections of colour samples. It has the special feature that, although an *objective* system, it is scaled *subjectively*. The Munsell notation for each colour sample is given in the form

HV/C (i.e. Hue, Value and Chroma).

Munsell Chroma: The parameter representing the amount of pure chromatic colour (as opposed to neutral colour) present in the specified sample. Munsell chroma is 0 for a neutral colour and ranges up to about 15 or 20 for the most highly saturated samples available in collections. (Theoretical maxima are about double these figures).

Munsell Hue: The parameter providing the systematic representation of that characteristic of a sample colour that denotes whether the colour appears red, yellow, green, blue, purple, etc. The usual notation employs 100 hue steps (e.g. 1R, 10YR, etc) in ten major hue regions (R, YR, Y, GY, G, BG, B, PB, P, RP).

Munsell Value: The parameter describing the degree of lightness of a specified sample colour. Munsell value ranges between 0 (for perfect black) and 10 (for perfect white) with subjectively equal steps in between.

NBS: National Bureau of Standards (USA).

Normal Trichromat: A trichromat whose visual colour matching conforms closely with that of the majority of observers.

NPRL: National Physical Research Laboratory (CSIR).

OB: Outside Broadcast.

Photopic Vision: Human vision in the light-adapted state, the chief characteristics of which are: sensitivity governed by the V_λ function; the perception of colour; and the perception of fine detail.

PIN: P-type/Intrinsic/N-type (photodiode).

Photomultiplier Tube: A vacuum-tube photoelectric cell employing a photoemissive cathode, which emits electrons in proportion to the incident irradiation, plus a series of secondary-emission electrodes (called dynodes) which provide amplification of the electron current before it reaches the anode. (Although the cathode response is a linear function of irradiance at any given wavelength, the magnitude of the response varies from one wavelength to another; hence the need for calibration by reference to a known spectrum).

PMT: Photomultiplier Tube.

Primary colours: The colours of (usually three) reference colour stimuli, the additive mixture of which, in appropriate proportions, is able to produce nearly all other colours.

Psychometric System: Applied to colorimetry: A three-dimensional space used for the representation of colours with the aim of providing perceptual uniformity of colour spacing.

Psychophysical System: Applied to colorimetry: A system by means of which colour may be measured by purely physical means (e.g. Photoelectric cells) but in which the transformation to meaningful colorimetric parameters is achieved by the use of standard spectral weighting functions (such as the CIE $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ colour-matching functions).

Psychosensorial: Referring to human response: A purely subjective response to a sensory stimulus.

Radiance: Of an area source: The apparent radiant intensity per unit projected area of an infinitesimal surface element on a radiating surface. Unit: watt per square metre per steradian.

Radiant Flux: Power emitted, transferred, or received as radiation. Unit: watt.

Radiant Intensity: Of a point source: The concentration of radiant flux per unit solid angle in an infinitesimal element of solid angle having its apex at the source. Unit: watt per steradian.

Retina: The light-sensitive layer of nerve-endings lining the inner surface of (roughly) the rear hemisphere of the eye.

Rods: The light-sensitive nerve-endings in the human retina, responsible for scotopic vision. They exist throughout the retina, except for the fovea, and appear to be of only one type.

RS–232: Standard drawn up by the Electronic Industries Association (USA) for serial digital communications.

RSA: Republic of South Africa.

Saturation: Subjective estimate of the amount of pure chromatic colour present in a colour sample, judged in relation to its brightness.

Scotopic Vision: Human vision in the dark-adapted state, the chief characteristics of which are: Sensitivity governed by the V'_λ function; greatly enhanced degree of light-sensitivity; enhanced ability to perceive fast movement or flashes of light; loss of colour perception; loss of detail perception; loss of foveal response.

Si: Silicon (chemical symbol).

S/N: Signal-to-Noise power ratio (of a detection system).

Solid Angle: The ratio of the area projected onto the surface of a sphere by a segment of three-dimensional space terminating in an apex at the centre of the sphere, to the square of the radius of the sphere. Unit: steradian.

SPD: Spectral Power Distribution (of radiation etc).

Spectral (Power) Distribution: Manner in which radiant flux, or other quantity, varies with wavelength, or frequency, over the spectrum.

Spectral Reflectance: The ratio of the reflected spectral radiant flux to the incident spectral radiant flux, for a specified geometry.

Spectral Stimulus Function: The quantity represented in a spectral (power) distribution.

Spectrum Locus: The locus in a chromaticity diagram that represents the range of visible monochromatic stimuli (for a normal human observer).

Steradian: The unit of solid angle.

TC: Technical Committee.

Trichromat: An observer whose colour response is three-dimensional.

Tristimulus Values X, Y, Z: Each tristimulus value is obtained as the correlation integral of the spectral stimulus function ($\phi_{e\lambda}$ say) with the relevant colour-matching function ($\bar{x}_\lambda$, $\bar{y}_\lambda$, or $\bar{z}_\lambda$ respectively).

TV: Television.

UCS: Uniform Chromaticity Scale.

UND: University of Natal at Durban.

Uniform-Chromaticity-Scale Diagram: A chromaticity diagram in which subjectively-equal chromaticity differences are represented by equal step sizes in all parts of the diagram.

Unique Hues: Red, green, blue and yellow: Hues that cannot be described in terms of other hues. They form two pairs which are mutually orthogonal in perceptual colour space.

USA: United States of America.

UV: Ultraviolet (radiation).

V_λ Function: Spectral sensitivity function of a normal human observer in the light-adapted state: originally defined for the CIE (1924) standard photometric observer, and identical to the $\bar{y}_\lambda$ colour matching function.

V'_λ Function: Spectral sensitivity function of a normal human observer in the dark-adapted state.

Watt: The unit of power, equal to energy transfer at a rate of 1 joule per second.

SYMBOLS, UNITS AND NOMENCLATURE

SI and Related Quantities

SYMBOL	QUANTITY	DIMENSIONS	UNIT	ABBREVIATION
-	Logarithmic Power Ratio	-	decibel	dB
E	Illuminance	$\mathrm{lm.\ m^{-2}}$	lux	lx
E_e	Irradiance	$\mathrm{W.\ m^{-2}}$	watt per square metre	$\mathrm{W/m^2}$
$E_{e\lambda}$	Spectral Irradiance	$\mathrm{W.m^{-2}.nm^{-1}}$	watt per square metre-nanometre	$\mathrm{W/m^2\text{-}nm}$
I	Luminous Intensity	$\mathrm{lm.sr^{-1}}$	Candela	cd
I_e	Radiant Intensity	$\mathrm{W.\ sr^{-1}}$	watt per steradian	W/sr
$I_{e\lambda}$	Spectral Radiant Intensity	$\mathrm{W.sr^{-1}.nm^{-1}}$	watt per steradian-nanometre	W/sr-nm

SI and Related Quantities (continued)

SYMBOL	QUANTITY	DIMENSIONS	UNIT	ABBREVIATION
L	Luminance	$lm.sr^{-1}.m^{-2}$	nit or, candela per square metre	nt cd/m^2
$L_{e\lambda}$	Spectral Radiance	$W.sr^{-1}.m^{-2}.nm^{-1}$	watt per steradian-square metre-nanometre	$W/sr\text{-}m^2\text{-}nm$
l	Length	m	metre	m
M	Exitance (Emitttance)	$lm.m^{-2}$	apostilb	asb
M_e	Radiant Exitance	$W.m^{-2}$	watt per square metre	W/m^2
$M_{e\lambda}$	Spectral Radiant Exitance	$W.m^{-2}.nm^{-1}$	watt per square metre-nanometre	$W/m^2\text{-}nm$
P	Power	$J.s^{-1}$	watt	W

SI and Related Quantities (continued)

SYMBOL	QUANTITY	DIMENSIONS	UNIT	ABBREVIATION
T	Thermodynamic Temperature	K	Kelvin	K
V	Electric Potential	$kg.m^2.A^{-1}.s^{-3}$	volt	V
η	Luminous Efficacy	$lm.W^{-1}$	lumen per watt	lm/W
λ	Wavelength (of optical radiation)	$m.10^{-9}$	nanometre	nm
ϕ	Luminous Flux	lm	lumen	lm
ϕ_e	Radiant Flux	$J.s^{-1}$	watt	W
$\phi_{e\lambda}$	Spectral Radiant Flux	$W.nm^{-1}$	watt per nanometre	W/nm
ω	Solid Angle	-	steradian	sr

Other Symbols Used in the Text

a_0, a_1 – Coefficients of linear regression

a^* – "Redness" coordinate in the CIE–1976 ($L^*a^*b^*$) colour space

b^* – "Yellowness" coordinate in the CIE–1976 ($L^*a^*b^*$) colour space

C – Munsell chroma

C^* – CIELAB chroma, defined by the equation $C^{*2} = a^{*2} + b^{*2}$

D_a – Colour rendering "demerit" of a test lamp defined as $D_a = 100 - R_a$ (Ch 5)

H – Munsell Hue

$L_{eo\lambda}$ – Spectral radiance of a reference source (Ch 4)

$L_{et\lambda}$ – Spectral radiance of a test source (Ch 4)

L^* – "Lightness" coordinate in CIELAB and CIELUV colour spaces

R_a – CIE general colour rendering index

$R_{eo\lambda}$ – Spectral reflectance factor of a reference surface (Ch 4)

$R_{et\lambda}$ – Spectral reflectance factor of a test surface (Ch 4)

r – Linear regression correlation coefficient

$s(L^*a^*b^*)$ – Standard deviation (in CIELAB coordinates) of colour measurements of a given sample (Ch 4)

$s(Y, u', v')$ – Standard deviation (in (Y, u', v') coordinates) of colour measurements of a given sample (Ch 4)

T_C – Correlated colour temperature of a light source

u – CIE–1960 UCS chromaticity coordinate : $u = 4X/(X+15Y+3Z)$

u'– CIE–1976 UCS chromaticity coordinate : $u' = u$

u^* – "Redness" coordinate in the CIE–1976 ($L^*u^*v^*$) colour space

V – Munsell Value (representing sample lightness)

V_λ – Spectral luminous efficiency for photopic vision (CIE standard observer)

V'_λ – Spectral luminous efficiency for scotopic vision

$V_{o\lambda}$ – Spectrophotometer output voltage at wavelength λ, with reference lamp or surface (Ch 4)

$V_{t\lambda}$ – Spectrophotometer output voltage at wavelength λ, with test lamp or surface (Ch 4)

v – CIE–1960 UCS chromaticity coordinate : $v = 6Y/(X+15Y+3Z)$

v'– CIE–1976 UCS chromaticity coordinate : $v' = 1{,}5v$

v^* – "Yellowness" coordinate in the CIE–1976 ($L^*u^*v^*$) colour space

X – CIE–1931 tristimulus value (correlating approximately with red content).

x – CIE–1931 chromaticity coordinate (correlating approximately with redness)

$\bar{x}$ (or $\bar{x}_\lambda$) – CIE–1931 colour-matching function

Y – CIE–1931 tristimulus value (correlating approximately with green content).

y – CIE–1931 chromaticity coordinate (correlating approximately with greenness).

$\bar{y}$ (or $\bar{y}_\lambda$) – CIE–1931 colour-matching function

Z – CIE–1931 tristimulus value (correlating approximately with blue content)

z – CIE–1931 chromaticity coordinate (correlating approximately with blueness)

$\bar{z}$ (or $\bar{z}_\lambda$) – CIE–1931 colour-matching function

ΔE^*(DM) – Variant of ΔE^* (Luv) with reduced lightness weighting, for assessment of colour reproductions

ΔE^* (Lab)
or
ΔE ($L^*a^*b^*$) – Colour difference between two points in CIELAB colour space

ΔE^* (Luv)
or
ΔE ($L^*u^*v^*$) – Colour difference between two points in CIELUV colour space

ΔE_1^* – A colour difference measuring the *fidelity* of colour reproduction for a specific test colour sample and test lamp (Ch 5)

ΔE_2^* – A colour difference measuring the *consistency* of colour reproduction for a specific test colour sample and test lamp (Ch 5)

$\overline{\Delta E^*}$ – An arithmetic mean colour difference

$\overline{\Delta E_1^*}$ – Mean colour difference measuring colour reproduction *fidelity* for a specific test lamp (Ch 5)

$\overline{\Delta E_2^*}$ – Mean colour difference measuring colour reproduction *consistency* for a specific test lamp (Ch 5)

ΔF – Abbreviated version of ΔF (u',v')

ΔF (u',v') – Chromaticity difference between two points in the CIE–1976 (u'v') diagram

ΔF_1 – Chromaticity difference measuring the *fidelity* of colour reproduction for a specific test colour sample and test lamp (Ch 5)

ΔF_2 – Chromaticity difference measuring the *consistency* of colour reproduction for a specific test colour sample and test lamp (Ch 5)

$\overline{\Delta F}$ – An arithmetic mean chromaticity difference

$\overline{\Delta F_1}$ – Mean chromaticity difference measuring colour reproduction fidelity (Ch 5)

$\overline{\Delta F_2}$ – Mean chromaticity difference measuring colour reproduction consistency (Ch 5)

ΔY – Luminance-factor-difference between two colours